IEC 62127-1

Edition 2.0 2022-03
REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Ultrasonics – Hydrophones –
Part 1: Measurement and characterization of medical ultrasonic fields ~~up to 40 MHz~~

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INTERNATIONAL
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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ULTRASONICS – HYDROPHONES –

Part 1: Measurement and characterization of medical ultrasonic fields ~~up to 40 MHz~~

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 62127-1:2007+AMD1:2013 CSV. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 62127-1 has been prepared by IEC technical committee 87: Ultrasonics. It is an International Standard.

This second edition cancels and replaces the first edition published in 2007 and Amendment 1:2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition.

a) The upper frequency limit of 40 MHz has been removed.
b) Hydrophone sensitivity definitions have been changed to recognize sensitivities as complex-valued quantities.
c) Procedures and requirements for narrow-band approximation and broadband measurements have been modified; details on waveform deconvolution have been added.
d) Procedures for spatial averaging correction have been amended.
e) Annex D, Annex E and bibliography have been updated to support the changes of the normative parts.

The text of this International Standard is based on the following documents:

Draft	Report on voting
87/783/FDIS	87/788/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of IEC 62127 series, published under the general title *Ultrasonics – Hydrophones*, can be found on the IEC website.

NOTE Words in **bold** in the text are terms defined in Clause 3.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The main purpose of this document is to define various acoustic parameters that can be used to specify and characterize ultrasonic fields propagating in liquids, and, in particular, water, using hydrophones. Measurement procedures are outlined that may be used to determine these parameters. Specific device related measurement standards, for example IEC 61689, IEC 61157, IEC 61847 or IEC 62359, can refer to this document for appropriate acoustic parameters. In IEC 62359, some additional measurement methods for attenuated parameters and indices are described addressing the specific needs of acoustic output characterization of ultrasonic diagnostic equipment in accordance with IEC 60601-2-37.

The philosophy behind this document is the specification of the acoustic field in terms of acoustic pressure parameters, acoustic pressure being the primary measurement quantity when hydrophones are used to characterize the field.

Intensity parameters are specified in this document, but these are regarded as derived quantities that are meaningful only under certain assumptions related to the ultrasonic field being measured.

ULTRASONICS – HYDROPHONES –

Part 1: Measurement and characterization of medical ultrasonic fields ~~up to 40 MHz~~

1 Scope ~~and object~~

This part of IEC 62127 specifies methods of use of calibrated **hydrophones** for the measurement in liquids of acoustic fields generated by ultrasonic medical equipment ~~operating in the frequency range up to 40 MHz~~ including **bandwidth** criteria and calibration frequency range requirements in dependence on the spectral content of the fields to be characterized.

This document:

- defines a group of acoustic parameters that can be measured on a physically sound basis;
- defines a second group of parameters that can be derived under certain assumptions from these measurements, and called derived intensity parameters;
- defines a measurement procedure that ~~may~~ can be used for the determination of acoustic pressure parameters;
- defines the conditions under which the measurements of acoustic parameters can be made ~~in the frequency range up to 40 MHz~~ using calibrated **hydrophones**;
- defines procedures for correcting for limitations caused by the use of **hydrophones** with finite **bandwidth** and finite active element size, and for estimating the corresponding **uncertainties**.

NOTE 1 Throughout this document, SI units are used. In the specification of certain parameters, such as **beam areas** and intensities, it ~~may~~ can be convenient to use decimal multiples or submultiples. For example, **beam area** ~~may~~ is likely to be specified in cm^2 and intensities in W/cm^2 or mW/cm^2.

NOTE 2 The **hydrophone** as defined ~~may~~ can be of a piezoelectric or an optic type.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

~~IEC 60050-801:1994, *International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics*~~

~~IEC 60565, *Underwater acoustics – Hydrophones – Calibration in the frequency range 0,01 Hz to 1 MHz*~~

IEC 60565-1, *Underwater acoustics – Hydrophones – Calibration of hydrophones – Part 1: Procedures for free-field calibration of hydrophones*

~~IEC/TR 60854:1986, *Methods of measuring the performance of ultrasonic pulse-echo diagnostic equipment*~~

IEC 61689, *Ultrasonics – Physiotherapy systems –* ~~*Performance requirements*~~ *Field specifications and methods of measurement in the frequency range 0,5 MHz to 5 MHz*

IEC 61828, *Ultrasonics – Focusing transducers – Definitions and measurement methods for the transmitted fields*

IEC 61846, *Ultrasonics – Pressure pulse lithotripters – Characteristics of fields*

IEC 61847, *Ultrasonics – Surgical systems – Measurement and declaration of the basic output characteristics*

IEC 62127-2, *Ultrasonics – Hydrophones – Part 2: Calibration for ultrasonic fields up to 40 MHz*

IEC 62127-3, *Ultrasonics – Hydrophones – Part 3: Properties of hydrophones for ultrasonic fields up to 40 MHz*

IEC 63009, *Ultrasonics – Physiotherapy systems – Field specifications and methods of measurement in the frequency range 20 kHz to 500 kHz*

ISO 16269-6:2005, *Statistical interpretation of data – Part 6: Determination of statistical tolerance intervals*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

NOTE The following standards rely on the proper use of this document.

IEC 61157, *Standard means for the reporting of the acoustic output of medical diagnostic ultrasonic equipment*

IEC 62359, *Ultrasonics – Field characterization – Test methods for the determination of thermal and mechanical indices related to medical diagnostic ultrasonic fields*

IEC 61847, *Ultrasonics – Surgical systems – Measurement and declaration of the basic output characteristics.*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62127-2, IEC 62127-3 and the following apply. It also includes definitions related to subjects in this document to be used in particular medical ultrasound device standards.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
acoustic pulse waveform
temporal waveform of the **instantaneous acoustic pressure** at a specified position in an acoustic field and displayed over a period sufficiently long to include all significant acoustic information in a single pulse or tone-burst, or one or more cycles in a continuous wave

Note 1 to entry: Temporal waveform is a representation (e.g. oscilloscope presentation or equation) of the **instantaneous acoustic pressure**.

3.2
acoustic repetition period
arp
pulse repetition period for non-automatic scanning systems and the **scan repetition period** for automatic scanning systems, equal to the time interval between corresponding points of consecutive cycles for continuous wave systems

Note 1 to entry: The **acoustic repetition period** is expressed in seconds (s).

3.3
acoustic-working frequency
acoustic frequency
frequency of an acoustic signal based on the observation of the output of a **hydrophone** placed in an acoustic field at the position corresponding to the **spatial-peak temporal-peak acoustic pressure**

Note 1 to entry: The signal is analysed using either the **zero-crossing acoustic-working frequency** technique or a spectrum analysis method. Acoustic-working frequencies are defined in 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.5.

Note 2 to entry: In a number of cases the present definition is not very helpful or convenient, especially for **broadband transducers**. In that case, a full description of the frequency spectrum should is expected to be given in order to enable any frequency-dependent correction to the signal.

Note 3 to entry: **Acoustic frequency** is expressed in hertz (Hz).

3.3.1
zero-crossing acoustic-working frequency
f_{awf}
number, n, of consecutive half-cycles (irrespective of polarity) divided by twice the time between the commencement of the first half-cycle and the end of the n-th half-cycle

Note 1 to entry: None of the n consecutive half-cycles should are expected to show evidence of phase change.

Note 2 to entry: The measurement should be are performed at terminals in the receiver that are as close as possible to the receiving transducer (**hydrophone**) and, in all cases, before rectification.

Note 3 to entry: This frequency is determined according to the procedure specified in IEC TR 60854.

Note 4 to entry: This frequency is intended for continuous-wave systems only.

3.3.2
arithmetic-mean acoustic-working frequency
f_{awf}
arithmetic mean of the most widely separated frequencies f_1 and f_2, within the range of three times f_1, at which the magnitude level of the acoustic pressure spectrum is 3 dB below the peak magnitude level

Note 1 to entry: This frequency is intended for pulse-wave systems only.

Note 2 to entry: It is assumed that $f_1 < f_2$.

Note 3 to entry: If f_2 is not found within the range $< 3f_1$, f_2 is to be understood as the lowest frequency above this range at which the spectrum magnitude level is 3 dB below the peak magnitude level.

3.3.3
magnitude-weighted acoustic-working frequency
f_{awf}
frequency weighted with the spectral acoustic pressure magnitude in the frequency range where the spectral pressure level is equal to or larger than 3 dB below the peak level

$$f_{awf} = \frac{\int f \left|\underline{P}(f)\right| \mathrm{d}f}{\int \left|\underline{P}(f)\right| \mathrm{d}f} \quad \text{with} \quad \left|\underline{P}(f)\right| = \begin{cases} \left|\underline{P}(f)\right| & \text{if } L_P(f) \geq \max L_P(f) - 3\,\mathrm{dB} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where

f is the frequency of the acoustic pressure spectrum;

$|\underline{P}(f)|$ is the modulus of the complex-valued spectrum of the **acoustic pulse waveform**;

$L_P(f)$ is the pressure level spectrum given from $L_P(f) = 20\log_{10}\left(\frac{|P(f)|}{P_{ref}}\right)$dB with P_{ref} = 1 Pa.

Note 1 to entry: This frequency is intended for pulse-wave systems only.

Note 2 to entry: The integrals in Formula (1) are definite, to be taken from the minimum to the maximum of the acquired signal spectrum.

Note 3 to entry: The restriction to the range with pressure levels equal to or larger than −3 dB of the peak level is required to avoid the influence of higher harmonic frequencies on the **acoustic-working frequency**.

Note 4 to entry: Definition 3.3.3 leads to more stable **acoustic-working frequency** results than definition 3.3.2 if there are peaks in the acoustic pressure spectrum close to the −3 dB threshold. This is particularly relevant for the determination of derated field parameters as required in IEC 62359 using a single derating factor depending on the **acoustic-working frequency**.

3.3.4
peak pulse acoustic frequency
f_p
~~arithmetic-mean~~ **acoustic-working frequency** of the pulse with the largest **peak negative acoustic pressure** measured at the point of maximum **peak negative acoustic pressure**

~~NOTE **Peak pulse acoustic frequency** is expressed in hertz (Hz).~~

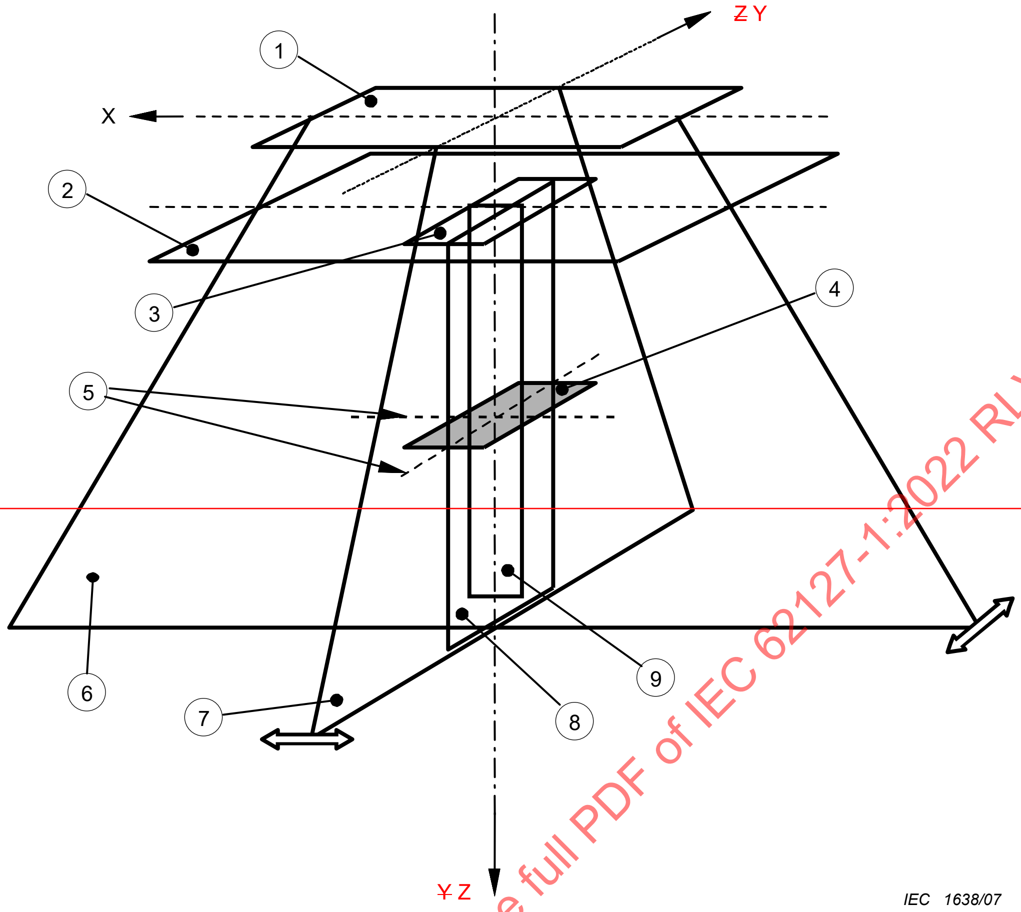
3.3.5
~~**time**~~ **temporal-average acoustic frequency**
f_t
~~**arithmetic-mean**~~ **acoustic-working frequency** of the time averaged acoustic pressure spectrum of the acoustic signals measured at the point of maximum **temporal-average intensity**

~~NOTE **Time average acoustic frequency** is expressed in hertz (Hz).~~

3.4
azimuth axis
axis formed by the junction of the **azimuth plane** and the **source aperture plane** (measurement) or **transducer aperture plane** (design)

SEE: Figure 1

[SOURCE: IEC 61828:~~2001~~2020, 3.7]



Key

X azimuth axis

Y elevation axis

Z beam axis

1 external transducer aperture plane

2 source aperture plane

3 aperture plane

4 beam area plane

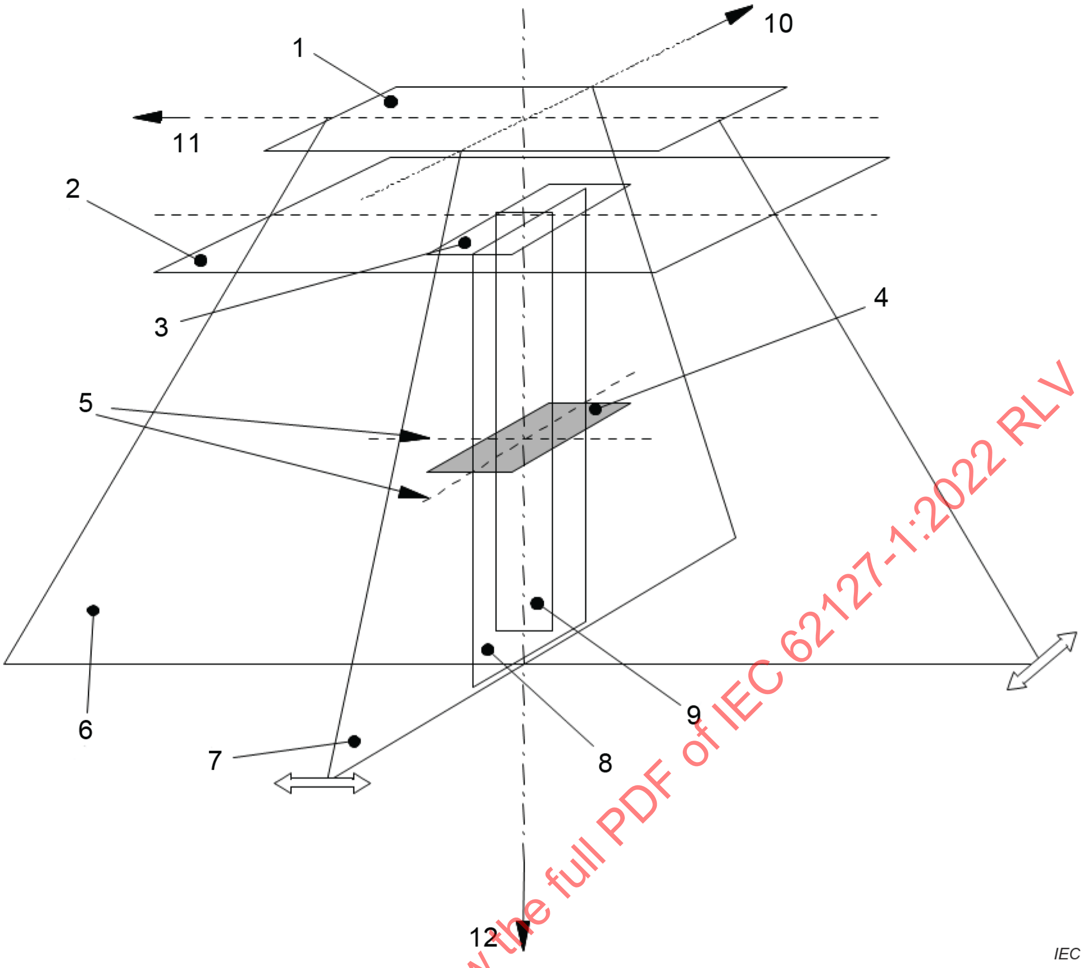
5 beamwidth lines

6 azimuth plane, scan plane

7 elevation plane

8 longitudinal plane

9 principle longitudinal plane



Key

1	external transducer surface plane	7	azimuth plane, scan plane
2	source aperture plane	8	principal longitudinal plane
3	source aperture	9	longitudinal plane
4	beam area plane	10	X, azimuth axis
5	beamwidth lines	11	Y, elevation axis
6	elevation plane	12	Z, beam axis

[SOURCE: IEC 61828:2020]

Figure 1 – Schematic diagram of the different planes and lines in an ultrasonic field

3.5
azimuth plane
~~for a scanning **ultrasonic transducer**: this is the **scan plane**; for a non-scanning **ultrasonic transducer**: this is the **principal longitudinal plane**~~
plane containing the **beam axis** and the line of the minimum **full width half maximum beamwidth**

SEE: Figure 1

Note 1 to entry: For an **ultrasonic transducer** array, this is the imaging plane.

Note 2 to entry: For a single **ultrasonic transducer** with spherical or circular symmetry, it is any plane containing the **beam axis**.

[SOURCE: IEC 61828:~~2001~~2020, 3.8]

3.6
bandwidth
BW
difference in the most widely separated frequencies f_1 and f_2 at which the ~~magnitude~~ level of the acoustic pressure spectrum becomes 3 dB below the peak ~~magnitude~~ level, at a specified point in the acoustic field

Note 1 to entry: **Bandwidth** is expressed in hertz (Hz).

3.7
beam area
$A_{b,6}$, $A_{b,20}$
area in a specified plane perpendicular to the **beam axis** consisting of all points at which the **pulse-pressure-squared integral** is greater than a specified fraction of the maximum value of the **pulse-pressure-squared integral** in that plane

Note 1 to entry: If the position of the plane is not specified, it is the plane passing through the point corresponding to the maximum value of the **pulse-pressure-squared integral** in the whole acoustic field.

Note 2 to entry: In a number of cases, the term **pulse-pressure-squared integral** is replaced everywhere in the above definition by any linearly related quantity, for example

a) in the case of a continuous wave signal the term **pulse-pressure-squared integral** is replaced by mean square acoustic pressure as defined in IEC 61689,

b) in cases where signal synchronization with the scanframe is not available the term **pulse-pressure-squared integral** may be replaced by **temporal average intensity.**

Note 3 to entry: Some specified fractions are 0,25 and 0,01 for the −6 dB and −20 dB beam areas, respectively.

Note 4 to entry: **Beam area** is expressed in units of metre squared (m^2).

~~NOTE 5 Definition is modified compared to that used in IEC 61828:2001.~~

3.8
beam axis
straight line that passes through the **beam centrepoints** of two planes perpendicular to the line which connects the point of maximal **pulse-pressure-squared integral** with the centre of the **external transducer aperture**

SEE: Figure 1

Note 1 to entry: The location of the first plane is the location of the plane containing the maximum **pulse-pressure-squared integral** or, alternatively, is one containing a single main lobe which is in the focal Fraunhofer zone. The location of the second plane is as far as is practicable from the first plane and parallel to the first with the same two orthogonal scan lines (x and y axes) used for the first plane.

Note 2 to entry: In a number of cases, the term **pulse-pressure-squared integral** is replaced in the above definition by any linearly related quantity, for example

a) in the case of a continuous wave signal the term **pulse-pressure-squared integral** is replaced by mean square acoustic pressure as defined in IEC 61689,

b) in cases where signal synchronization with the scanframe is not available the term **pulse-pressure-squared integral** may be replaced by **temporal average intensity**.

~~NOTE 4 Definition is modified compared to that used in IEC 61828:2001.~~

3.9
beam centrepoint
position determined by the intersection of two lines in the same beam area plane xy passing through the **beamwidth midpoints** of two orthogonal planes, xz and yz, perpendicular to their respective beamwidth lines

[SOURCE: IEC 61828:~~2001~~2020, 3.15, modified – In the definition, "in the same beam area plane xy" and ", perpendicular to their respective beamwidth lines" have been added.]

3.10
beamwidth midpoint
linear average of the location of the centres of **beamwidth**s in a plane

Note 1 to entry: The **beamwidth** midpoint method is described in Annex K.

Note 2 to entry: The average is taken over as many **beamwidth** levels given in Table K.1 as signal level permits.

[SOURCE: IEC 61828:~~2001~~2020, 3.22, modified – Note 1 to entry has been replaced by new Notes to entry.]

3.11
beamwidth
w_6, w_{12}, w_{20}
greatest distance between two points on a specified axis perpendicular to the **beam axis** where the **pulse-pressure-squared integral** falls below its maximum on the specified axis by a specified amount

Note 1 to entry: In a number of cases, the term **pulse-pressure-squared integral** is replaced in the above definition by any linearly related quantity, for example

a) in the case of a continuous wave signal the term **pulse-pressure-squared integral** is replaced by mean square acoustic pressure as defined in IEC 61689,

b) in cases where signal synchronization with the scanframe is not available the term **pulse-pressure-squared integral** ~~may~~ can be replaced by **temporal average intensity**.

Note 2 to entry: Commonly used **beamwidths** are specified at −6 dB, −12 dB and −20 dB levels below the maximum. The decibel calculation implies taking 10 times the logarithm of the ratios of the integrals.

Note 3 to entry: **Beamwidth** is expressed in metres (m).

~~NOTE 4 Definition slightly modified to that in IEC 61828:2001.~~

3.12
broadband transducer
transducer that generates an acoustic pulse of which the **bandwidth** is greater than the ~~**arithmetic-mean**~~ **acoustic-working frequency**

3.13
central scan line
<for automatic scanning systems> **ultrasonic scan line** closest to the symmetry axis of the **scan plane**

3.14
derived instantaneous intensity
quotient of squared **instantaneous acoustic pressure** and characteristic acoustic impedance of the medium at a particular instant in time at a particular point in an acoustic field

$$I(t) = \frac{p(t)^2}{\rho c} \tag{2}$$

where:

$p(t)$ is the **instantaneous acoustic pressure**;

ρ is the density of the medium;

c is the speed of sound in the medium

Note 1 to entry: For measurement purposes referred to in this document, the **derived instantaneous intensity** is an approximation of the **instantaneous intensity**.

Note 2 to entry: Increased uncertainty ~~should~~ is expected to be taken into account for measurements very close to the transducer.

Note 3 to entry: **Derived instantaneous intensity** is expressed in units of watt per metre squared (W/m^2).

3.15
diametrical beam scan
set of measurements of the **hydrophone** output voltage made while moving the **hydrophone** in a straight line passing through a point on the **beam axis** and in a direction normal to the **beam axis**

Note 1 to entry: The **diametrical beam scan** ~~may~~ can extend to different distances on either side of the **beam axis**.

3.16
distance z_r
z_r
distance along the **beam axis** between the plane containing the **peak-rarefactional acoustic pressure** and the **external transducer aperture**

Note 1 to entry: The **distance** z_r is expressed in metres (m).

3.17
distance z_c
z_c
distance along the **beam axis** between the plane containing the **peak-compressional acoustic pressure** and the **external transducer aperture**

Note 1 to entry: The **distance** z_c is expressed in metres (m).

3.18
distance z_{ppsi}
z_{ppsi}
distance along the **beam axis** between the plane containing the maximum **pulse-pressure-squared integral** and the **external transducer aperture**

Note 1 to entry: The **distance** z_{ppsi} is expressed in metres (m).

3.19
distance z_spta
z_spta
distance along the **beam axis** between the plane containing the **spatial-peak temporal-average intensity** and the **external transducer aperture**

Note 1 to entry: In practice, this distance is equal to the distance z_{ppsi}.

Note 2 to entry: The **distance** z_spta is expressed in metres (m).

~~**3.19**~~
~~**distance z_offset**~~
~~z_offset~~
~~distance along the **beam axis** between the plane containing the active face of the ultrasonic transducer or ultrasonic transducer element group and the **external transducer aperture**~~

~~NOTE 1 **Distance z_offset** is expressed in metres (m).~~

~~NOTE 2 Definition adopted, with modified symbol, from IEC 61828:2001.~~

3.20
effective hydrophone ~~radius~~ size
a_h, ~~a_{h3}, a_{h6}~~
~~radius~~ size of a ~~stiff disc~~ theoretical receiver **hydrophone** that has a predicted **directional response** function with an angular width equal to the observed angular width

~~NOTE 1 The angular width is determined at a specified level below the peak of the **directional response** function. For the specified levels of 3 dB and 6 dB, the radii are denoted by a_{h3} and a_{h6} respectively.~~

~~NOTE 3 The radius is usually the function of frequency. For representative experimental data, see [].~~

~~NOTE 4 Definition adopted from IEC 62127-3.~~

Note 1 to entry: The size is usually a function of frequency. For representative experimental data, see [1].

Note 2 to entry: The **effective hydrophone ~~radius~~ size** is expressed in metres (m).

Note 3 to entry: For hydrophones with a circular geometry, the **effective hydrophone size** is a radius.

Note 4 to entry: For hydrophones with a rectangular geometry, the **effective hydrophone size** is the half of the largest value of the length or width.

[SOURCE: IEC 62127-3:2007, 3.2, modified – In the term, "radius" has been replaced with "size". In the definition, "radius of a stiff disc receiver" has been replaced with "size of a theoretical receiver". The NOTES have been replaced.]

3.21
effective radius of a non-focusing ultrasonic transducer
a_t
radius of a perfect disc piston-like **ultrasonic transducer** that has a predicted axial acoustic pressure distribution approximately equivalent to the observed axial acoustic pressure distribution over an axial distance until at least the last axial maximum has passed

Note 1 to entry: The **effective radius of a non-focusing ultrasonic transducer** is expressed in metres (m).

3.22
electric load impedance
$\underline{Z}_L$
complex electric input impedance (consisting of a real and an imaginary part) to which the **hydrophone** unit output cable is connected or is intended to be connected

Note 1 to entry: The **electric load impedance** is expressed in ohms (Ω).

[SOURCE: IEC 62127-3:2007, 3.3, modified – In the definition, "**hydrophone** or **hydrophone assembly** output" has been replaced by "**hydrophone** unit output cable".]

3.23
elevation axis
line in the **source aperture plane** (measurement) or **transducer aperture plane** (design) that is perpendicular to the **azimuth axis** and the **beam axis**

SEE: Figure 1

[SOURCE: IEC 61828:~~2001~~2020, 3.48, modified – Notes to entry have been omitted.]

3.24
elevation plane
longitudinal plane containing the **elevation axis**

SEE: Figure 1

[SOURCE: IEC 61828:~~2001~~2020, 3.49, modified – The words "and the beam axis" have been deleted since this is already included in the definition of longitudinal plane.]

3.25
end-of-cable loaded sensitivity
$\underline{M}_L(f)$
<of a **hydrophone** or **hydrophone assembly**> ~~ratio~~ quotient of the ~~instantaneous~~ Fourier transformed **hydrophone** voltage-time signal $\mathcal{F}(u_L(t))$ at the end of any integral cable or output connector of a **hydrophone** or **hydrophone assembly**, when connected to a specified **electric load impedance**, to the ~~**instantaneous**~~ Fourier transformed **acoustic** ~~**pressure**~~ **pulse waveform** $\mathcal{F}(p(t))$ in the undisturbed free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_L(f) = \frac{\mathcal{F}(u_L(t))}{\mathcal{F}(p(t))} \tag{3}$$

Note 1 to entry: The **end-of-cable loaded sensitivity** is a complex-valued parameter. Its modulus is expressed in units of volt per pascal (V/Pa), its phase angle is expressed in degrees, and represents the phase difference between the electrical voltage and the sound pressure.

~~NOTE 2 Definition adopted from IEC 62127-3.~~

3.26
end-of-cable loaded sensitivity level
$L_{M_L}(f)$
<of a **hydrophone** or **hydrophone assembly**> twenty times the logarithm to the base 10 of the quotient of the modulus of the **end-of-cable loaded sensitivity** $|\underline{M}_L(f)|$ to a reference sensitivity M_{ref}

$$L_{M_L}(f) = 20\log_{10}\frac{|\underline{M}_L(f)|}{M_{ref}}\,\text{dB} \tag{4}$$

Note 1 to entry: Commonly used values of the reference sensitivity M_{ref} are 1 V/µPa or 1 V/Pa.

Note 2 to entry: The **end-of-cable loaded sensitivity level** is expressed in decibels (dB).

3.27
end-of-cable open-circuit sensitivity
$\underline{M}_c(f)$
<of a **hydrophone**> ~~ratio~~ quotient of the ~~instantaneous~~ Fourier transformed **hydrophone** open-circuit voltage-time signal $\mathcal{F}(u_c(t))$ at the end of any integral cable or output connector of a **hydrophone** to the ~~**instantaneous**~~ Fourier transformed **acoustic** ~~**pressure**~~ **pulse waveform** $\mathcal{F}(p(t))$ in the undisturbed free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_c(f) = \frac{\mathcal{F}(u_c(t))}{\mathcal{F}(p(t))} \tag{5}$$

Note 1 to entry: The **end-of-cable open-circuit sensitivity** is a complex-valued parameter. Its modulus is expressed in units of volt per pascal (V/Pa), its phase angle is expressed in degrees, and represents the phase difference between the electrical voltage and the sound pressure.

NOTE 2 Definition adopted from IEC 62127-3.

3.28
external transducer surface
external transducer aperture
part of the surface of the **ultrasonic transducer** or **ultrasonic transducer element group** assembly that emits ultrasonic radiation into the propagation medium

SEE: Figure 1

Note 1 to entry: This surface is assumed to be accessible for measurements using a hydrophone in a chosen propagation medium (usually water).

Note 2 to entry: This surface is either directly in contact with the patient or is in contact with a water or liquid path to the patient.

[SOURCE: IEC 61828:20012020, 3.52]

3.29
external transducer surface plane
external transducer aperture plane
plane that is orthogonal to the **beam axis** of the unsteered beam, or the axis of symmetry of the **azimuth plane** for an automatic scanner, and is adjacent physically to the **ultrasonic transducer** and **external transducer surface**

SEE: Figure 2

Note 1 to entry: If the **ultrasonic transducer** is flat, the plane is coplanar with the radiating surface of the **ultrasonic transducer**; if it is concave, the plane touches the periphery of the radiating surface; if it is convex, the plane is tangent to the centre of the radiating surface at the point of contact.

[SOURCE: IEC 61828:2020, 3.53]

3.30
far field
region of the field where $z > z_T$ aligned along the **beam axis** for planar non-focusing transducers

Note 1 to entry: In the **far field**, the sound pressure appears to be spherically divergent from a point on or near the radiating surface. Hence the pressure produced by the sound source is approximately inversely proportional to the distance from the source.

Note 2 to entry: The term **far field** is used in this document only in connection with non-focusing source transducers. For focusing transducers, a different terminology for the various parts of the transmitted field applies (see IEC 61828).

Note 3 to entry: If the shape of the transducer aperture produces several **transition distances**, the one furthest from the transducer is used.

3.31
hydrophone geometrical radius
a_g
radius defined by the dimensions of the active element of a **hydrophone**

Note 1 to entry: The **hydrophone geometrical radius** is expressed in metres (m).

[SOURCE: IEC 62127-3:2007, 3.8]

3.32
hydrophone
transducer that produces electric signals in response to waterborne acoustic signals pressure fluctuations in water

Note 1 to entry: A **hydrophone** is principally a passive device designed and built to respond to sound pressure.

Note 2 to entry: In some applications, a **hydrophone** is used as an active device to transmit sound.

[SOURCE: IEC 60050-801:2021, 801-32-26]

3.33
hydrophone assembly
combination of **hydrophone** and **hydrophone pre-amplifier**

[SOURCE: IEC 62127-3:2007, 3.10]

3.34
hydrophone pre-amplifier
active electronic device connected to, or to be connected to, a particular **hydrophone** and reducing its output impedance

Note 1 to entry: A **hydrophone pre-amplifier** requires a supply voltage (or supply voltages).

Note 2 to entry: The **hydrophone pre-amplifier** may have a forward voltage transmission factor of less than one, i.e. it need not necessarily be a voltage amplifier in the strict sense.

[SOURCE: IEC 62127-3:2007, 3.12]

3.35
instantaneous acoustic pressure
$p(t)$
pressure at a particular instant in time and at a particular point in an acoustic field ~~(see also IEV 801-01-19)~~, minus the ambient pressure

Note 1 to entry: **Instantaneous acoustic pressure** is expressed in pascals (Pa).

[SOURCE: IEC 60050-802:2011, 802-01-03]

3.36
instantaneous intensity
$I(t)$
acoustic energy transmitted per unit time in the direction of acoustic wave propagation per unit area normal to this direction at a particular instant in time and at a particular point in an acoustic field

Note 1 to entry: **Instantaneous intensity** is the product of **instantaneous acoustic pressure** and particle velocity. It is difficult to measure intensity in the ultrasound frequency range. For the measurement purposes referred to in this document and under conditions of sufficient distance from the **external transducer aperture** (at least one transducer diameter, or an equivalent transducer dimension in the case of a non-circular transducer) the **instantaneous intensity** can be approximated by the **derived instantaneous intensity.**

Note 2 to entry: **Instantaneous intensity** is expressed in units of watt per metre squared (W/m²).

3.37
local area factor
F_a
square root of the ratio of the **source aperture area** to the **beam area** at the point of interest

$$F_a = \sqrt{\frac{A_{SAeff}}{A_b}} \quad (6)$$

Note 1 to entry: The relevant local **beam area**, A_b, is that for which the **pulse-pressure-squared integral** is greater than 0,135 (that is, $1/e^2$) times the maximum value in the cross-section.

Note 2 to entry: If the beam profile is approximately Gaussian at the distance of interest and the area at the −6dB level, $A_{b,-6dB}$ $A_{b,6}$, is known, the local **beam area** can be calculated as

$A_b = A_{b,-6dB}$ $A_{b,6}$/0,69: (0,69 = 3ln(10)/10) $F_a = \sqrt{\frac{0{,}69 A_{SAeff}}{A_{b,6}}}$.

[SOURCE: IEC TS 61949:2007, 3.11, modified – "source aperture" has been replaced by "source aperture area"; the formula for the general case has been added; the second sentence of the original definition has been moved to a Note 1 to entry; the third sentence of the original definition has been changed into a Note 2 to entry and provides more details and the symbol for the −6 dB **beam area** was changed to conform with Clause 4.]

3.38
local distortion parameter

σ_q

index which permits the prediction of nonlinear distortion of ultrasound for a specific **ultrasonic transducer**, and is given by σ_q from:

$$\sigma_q = z\, p_m \frac{2\pi f_{awf} \beta}{\rho \cdot c^3} \frac{1}{\sqrt{F_a}} \qquad (7)$$

where

- z is the axial distance of the point of interest to the transducer face;
- p_m is the **mean-peak acoustic pressure** at the point in the acoustic field corresponding to the **spatial-peak temporal-peak acoustic pressure**;
- β is the nonlinearity parameter (β = 1 + $B/2A$ = 3,5 for pure water at 20 °C);
- f_{awf} is the **acoustic-working frequency**;
- F_a is the **local area factor**.

Note 1 to entry: If the transmitting system comprises an internal standoff utilizing a water or water-equivalent propagation medium, the offset distance between the transducer element and the transducer face increases the actual path length z to be considered. The nominal distance between the **beam axis**'s intersection with the crystal and the transducer face can be used.

[SOURCE: IEC TS 61949:2007, 3.12, modified – The text of the definition has changed substantially, the formula however is unchanged; Note 1 to entry has been added.]

3.39
longitudinal plane

plane defined by the **beam axis** and a specified orthogonal axis

SEE: Figure 1

NOTE 1 Definition adopted from IEC 61828:2001, 4.2.43.

3.40
mean peak acoustic pressure

p_m

arithmetic mean of the **peak-rarefactional acoustic pressure** and the **peak-compressional acoustic pressure**

Note 1 to entry: **Mean peak acoustic pressure** is expressed in pascals (Pa).

[SOURCE: IEC TS 61949:2007, 3.13, modified – Note 1 to entry has been added.]

3.41
near field
region of the field where $z < z_T$ aligned along the **beam axis** for planar non-focusing transducers

Note 1 to entry: For circular planar transducers, this is at a distance less than $A_{ob}/\pi\lambda$, where A_{ob} is the **output beam area** and λ is the wavelength of the ultrasound corresponding to the **acoustic frequency**.

Note 2 to entry: If the shape of the transducer aperture produces several **transition distances**, the one closest to the transducer ~~shall be~~ is used.

3.42
number of pulses per ultrasonic scan line
n_{pps}
number of acoustic pulses travelling along a particular **ultrasonic scan line**

Note 1 to entry: Here **ultrasonic scan line** refers to the path of acoustic pulses on a particular **beam axis** in **scanning modes** and **non-scanning modes**.

Note 2 to entry: This number can be used in the calculation of any ultrasound temporal average value from **hydrophone** measurements.

Note 3 to entry: The following shows an example of the **number of pulses per ultrasonic scanline** and the **number of ultrasonic scanlines** (shows the end of a frame):

1 2 3 4; 1 2 3 4; 1 2 3 4… n_{pps} = 1; n_{sl} = 4
1 1 2 2 3 3 4 4; 1 1 2 2 3 3 4 4; … n_{pps} = 2; n_{sl} = 4
1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4; 1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4; … n_{pps} = 4; n_{sl} = 4
~~1 1 2 2 3 3 4 4 1 1 2 2 3 3 4 4; 1 1 2 2 3 3 4 4 1 1 2 2 3 3 4 4; … n_{pps} = 4; n_{sl} = 4~~
1 1 2 2 3 3 4 4 1 1 1 2 2 2 3 3 3 4 4 4; 1 1 2 2 3 3 4 4 1 1 1 2 2 2 3 3 3 4 4 4; … n_{pps} = 5; n_{sl} = 4 (within one frame the pulses down each line may not occur contiguously)

Note 4 to entry: Within one frame, all scan lines ~~may~~ possibly do not have the same n_{pps} value.
An example is: 1 2 2 3 3 4; 1 2 2 3 3 4; … avg n_{pps} =1,5; max n_{pps} = 2; n_{sl}= 4

[SOURCE: IEC 61157:2007/AMD1:2013, 3.45 modified – the fourth example in Note 3 to entry has been corrected and the last example has been moved to a Note 4 to entry.]

3.43
number of ultrasonic scan lines
n_{sl}
~~the **number**~~ quantity of **ultrasonic scan lines** that are excited during one **scan repetition period**

Note 1 to entry: This number can be used in the calculation of ~~any ultrasound~~ temporal average values for **scanning modes** from **hydrophone** measurements.

[SOURCE: IEC 61157:2007/AMD1:2013, 3.46]

3.44
offset distance
d_{offset}
distance between the **source aperture plane** and the **external transducer surface plane**, measured along the **beam axis**

SEE: Figure 2

Note 1 to entry: **Offset distance** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.90]

3.45
operating mode
mode of operation of a **system**

3.45.1
combined-operating mode
operating **mode** ~~of operation of a **system**~~ that combines more than one **discrete-operating mode**

Note 1 to entry: Examples of **combined-operating modes** are real-time B-mode combined with M-mode (B+M), real-time B-mode combined with pulsed Doppler (B+D), colour M-mode (cM), real-time B-mode combined with M-mode and pulsed Doppler (B+M+D), real-time B-mode combined with real-time flow-mapping Doppler (B+rD), i.e. flow-mapping in which different types of acoustic pulses are used to generate the Doppler information and the imaging information.

3.45.2
discrete-operating mode
operating **mode** ~~of operation~~ of **medical diagnostic ultrasonic equipment** in which the purpose of the excitation of the **ultrasonic transducer** or **ultrasonic transducer element group** is to utilize only one diagnostic methodology

Note 1 to entry: Examples of **discrete-operating modes** are A-mode (A), M-mode (M), static B-mode (sB), real-time B-mode (B), continuous wave Doppler (cwD), pulsed Doppler (D), static flow-mapping (sD) and real-time flow-mapping Doppler (rD) using only one type of acoustic pulse.

3.45.3
inclusive mode
combined-operating mode having acoustic output levels (p_r and I_{spta}) less than those corresponding to a specified **discrete-operating mode**

3.45.4
non-scanning mode
operating **mode** ~~of operation of a **system**~~ that involves a sequence of ultrasonic pulses which give rise to **ultrasonic scan lines** that follow the same acoustic path

3.45.5
scanning mode
operating **mode** ~~of operation of a **system**~~ that involves a sequence of ultrasonic pulses which give rise to **ultrasonic scan lines** that do not follow the same acoustic path

~~NOTE The sequence of pulses is not necessarily made up of identical pulses. For instance, the use of sequential multiple focal-zones is considered a scanning mode.~~

3.46
output beam area
A_{ob}
area of the ultrasonic beam derived from the −12 dB **beam area** at the **external transducer aperture**

Note 1 to entry: For reasons of measurement accuracy, the −12 dB **output beam area** ~~may be~~ is derived from measurements at a distance chosen to be as close as possible to the face of the transducer, and, if possible, no more than 1 mm from the face.

Note 2 to entry: For contact transducers, this area can be taken as the geometrical area of the **ultrasonic transducer** or **ultrasonic transducer element group**.

Note 3 to entry: The **output beam area** is expressed in units of metre squared (m^2).

3.47
output beam dimensions
X_{ob}, Y_{ob}
dimensions of the ultrasonic beam (−12 dB **beamwidth**) in specified directions perpendicular to each other and in a direction normal to the **beam axis** and at the **external transducer aperture**

Note 1 to entry: For reasons of measurement accuracy, the −12 dB **output beam dimensions** may be is derived from measurements at a distance chosen to be as close as possible to the face of the transducer, and, if possible, no more than 1 mm from the face.

Note 2 to entry: For contact transducers, these dimensions can be taken as the geometrical dimensions of the **ultrasonic transducer** or **ultrasonic transducer element group**.

Note 3 to entry: **Output beam dimensions** are expressed in metres (m).

3.48
output beam intensity
I_{ob}
temporal-average power output divided by the **output beam area**

Note 1 to entry: **Output beam intensity** is expressed in units of watt per metre squared (W/m^2).

3.49
peak acoustic pressure
p_c (or p_+) or p_r (or p_-)
peak-compressional acoustic pressure or **peak-rarefactional acoustic pressure**

NOTE 1 The term is used in relative determinations.

Note 1 to entry: **Peak acoustic pressure** is expressed in pascals (Pa).

3.50
peak-compressional acoustic pressure
p_c (or p_+)
maximum positive **instantaneous acoustic pressure** in an acoustic field or in a specified plane during an **acoustic repetition period**

Note 1 to entry: **Peak-compressional acoustic pressure** is expressed in pascals (Pa).

Note 2 to entry: The definition of **peak-compressional acoustic pressure** also applies to peak-positive acoustic pressure, which is also in use in literature.

3.51
peak-rarefactional acoustic pressure
p_r (or p_-)
maximum of the modulus of the negative **instantaneous acoustic pressure** in an acoustic field or in a specified plane during an **acoustic repetition period**

Note 1 to entry: **Peak-rarefactional acoustic pressure** is expressed as using a positive number for the numerical value.

Note 2 to entry: **Peak-rarefactional acoustic pressure** is expressed in pascals (Pa).

Note 3 to entry: The definition of **peak-rarefactional acoustic pressure** also applies to peak-negative acoustic pressure, which is also in use in literature.

3.52
principal longitudinal plane
plane containing the **beam axis** and two points that define the minimum −6 dB **beamwidth**

SEE: Figure 1

Note 1 to entry: The selection of this axis is arbitrary for a circularly-symmetric transducer.

Note 2 to entry: For a HITU transducer with a hole in its centre within which is a diagnostic imaging transducer, this axis is aligned with the azimuth axis of the imaging transducer.

Note 3 to entry: For rectangular **ultrasonic transducers**, it is the plane parallel to their longest side.

[SOURCE: IEC 61828:2020, 3.110 modified – the reference to HITU transducers has been deleted in Note 1 to entry.]

3.53
pulse-average intensity
I_{pa}
quotient of the **pulse-intensity integral** to the **pulse duration** at a particular point in an acoustic field

Note 1 to entry: This definition applies to pulses and bursts.

Note 2 to entry: **Pulse-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.54
pulse duration
t_d
1,25 times the interval between the time when the time integral of the square of the **instantaneous acoustic pressure** reaches 10 % and 90 % of its final value

SEE: Figure 4

Note 1 to entry: The final value of the time integral of the square of the **instantaneous acoustic pressure** is the **pulse-pressure-squared integral**.

Note 2 to entry: **Pulse duration** is expressed in seconds (s).

3.55
pulse-intensity integral
pii
time integral of the **instantaneous intensity** at a particular point in an acoustic field integrated over the **acoustic pulse waveform**

Note 1 to entry: For measurement purposes referred to in this document, **pulse-intensity integral** is proportional to **pulse-pressure-squared integral**.

Note 2 to entry: The **pulse-intensity integral** is expressed in units of joule per metre squared (J/m^2).

3.56
pulse-pressure-squared integral
ppsi
time integral of the square of the **instantaneous acoustic pressure** at a particular point in an acoustic field integrated over the **acoustic pulse waveform**

Note 1 to entry: The **pulse-pressure-squared integral** is expressed in units of pascal squared times second (Pa^2s).

3.57
pulse repetition period
prp
time interval between equivalent points on successive pulses or tone-bursts of pulses comprising a **discrete operating mode**

~~NOTE 1 This applies to single element non-automatic scanning systems and automatic scanning systems.~~

Note 1 to entry: The **pulse repetition period** is expressed in seconds (s).

3.58
pulse repetition rate
prr
reciprocal of the **pulse repetition period**

Note 1 to entry: The **pulse repetition rate** is expressed in hertz (Hz).

3.59
reference centre
<of a **hydrophone**> point on, within or near a **hydrophone** about which its electro-acoustic characteristics are defined

Note 1 to entry: The **reference centre** often corresponds to the geometrical centre of a **hydrophone** active element, unless otherwise stated.

[SOURCE: IEC 60500:2017, 3.26, modified – The context <of a **hydrophone**> and the term "active element" in Note 1 to entry have been added. In the definition, the word "geometrical" has been deleted.]

3.60
RMS acoustic pressure
p_{RMS}
root-mean-square (RMS) of the **instantaneous acoustic pressure** at a particular point in an acoustic field

Note 1 to entry: The mean should be taken over an integral number of **acoustic repetition periods** unless otherwise specified.

Note 2 to entry: **RMS acoustic pressure** is expressed in pascals (Pa).

3.61
scan-area
A_{s}
<for automatic scanning systems> area on a specified plane (or surface) consisting of all points within the **beam area** of any beam passing through the surface during the scan

Note 1 to entry: The specified plane (or surface) follows the same shape as the **external transducer aperture**.

Note 2 to entry: The **scan-area** is expressed in units of metre squared (m^2).

3.62
scan plane
<for automatic scanning systems> plane containing all the **ultrasonic scan lines**

~~NOTE 1 See Figure 1.~~

Note 1 to entry: Some scanning systems have the ability to steer the ultrasound beam in two directions. In this case, there is no **scan plane** that meets this definition. However, it might be useful to consider a plane through the major-axis of symmetry of the ~~ultrasound~~ **ultrasonic transducer** and perpendicular to the transducer face (or another suitable plane) as being equivalent to the **scan plane**.

3.63
scan repetition period
srp
<for automatic scanning systems with a periodic scan sequence> time interval between identical points on two successive frames, sectors or scans

Note 1 to entry: In general, this document assumes that an individual scan line repeats exactly after a number of acoustic pulses. In case an **ultrasonic transducer** or **ultrasonic transducer element group** radiates ultrasound without any sequence of repetition, it will not be possible to characterize a scanned mode in the way described in this document. The approach described in Annex F can be useful when synchronization cannot be achieved.

Note 2 to entry: The **scan repetition period** is expressed in seconds (s).

3.64
scan repetition rate
srr
reciprocal of the **scan repetition period**

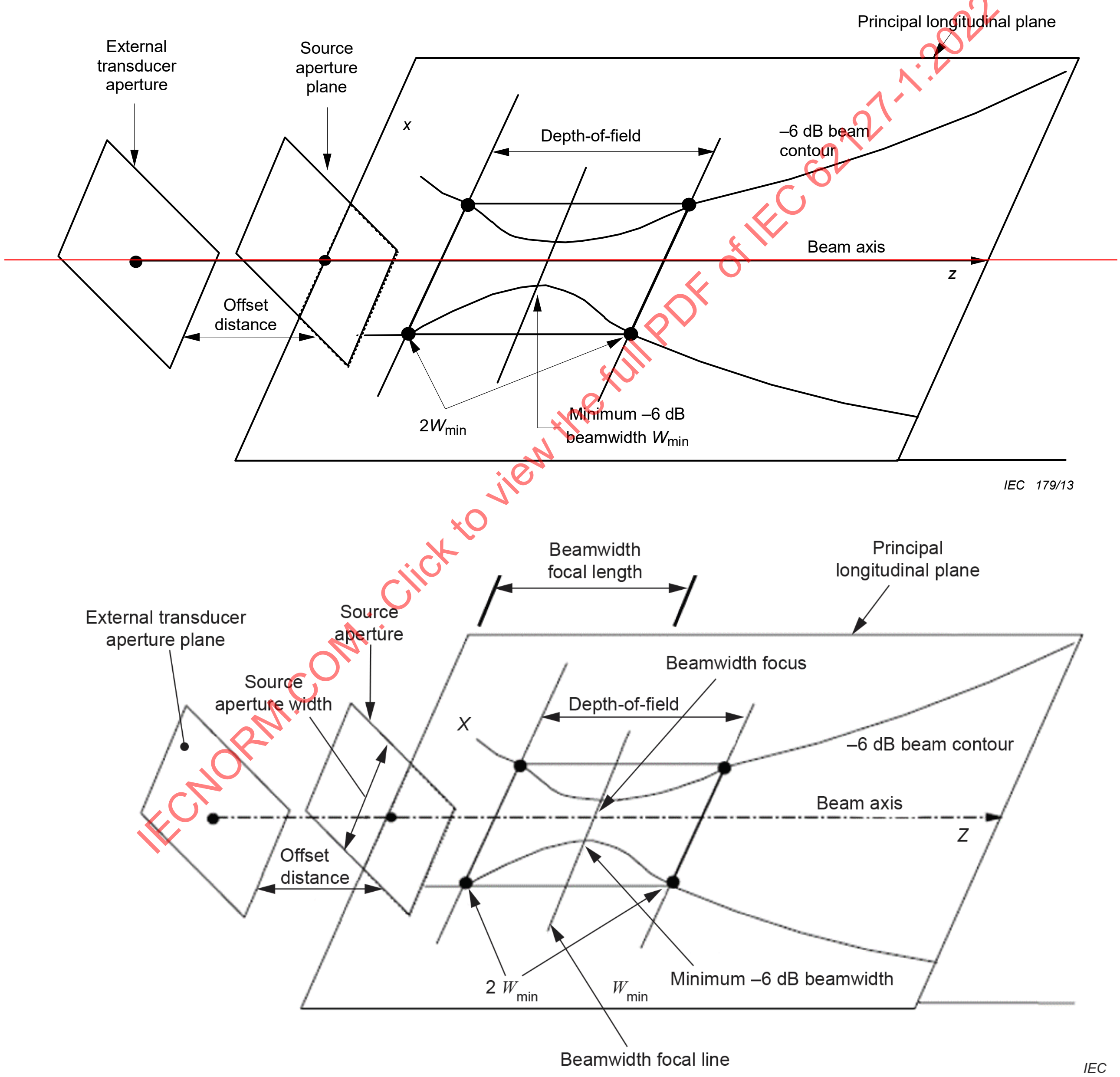
Note 1 to entry: The **scan repetition rate** is expressed in hertz (Hz).

3.65
source aperture area
A_{SAeff}
equivalent aperture area for an **ultrasonic transducer** of unknown characteristics, measured as the area inside the −20 dB **pulse-pressure-squared-integral** contour in the closest possible measurement plane (source aperture plane) to the **external transducer aperture**

SEE: Figure 2

Note 1 to entry: The nominal transmitting area of the source can be used for the calculation of the **local distortion parameter** σ_q in cases where there is a significant offset between the transducer crystal and the front face due to an internal standoff.

Note 2 to entry: **Source aperture area** is expressed in units of metre squared (m²).



[SOURCE: IEC 61828:2020]

Figure 2 – Several apertures and planes for a transducer of unknown geometry

3.66
source aperture plane
closest possible measurement plane to the **external transducer** ~~aperture~~ **surface plane** that is perpendicular to the **beam axis**

SEE: Figure 2

Note 1 to entry: If the **offset distance** is zero, the **source aperture plane** can be coincident with the **external transducer aperture plane**.

[SOURCE: IEC 61828:~~2006~~2020, 3.135]

3.67
source aperture width
L_{SA}
<in a specified **longitudinal plane**> greatest −20 dB **beamwidth** along the line of intersection between the designated **longitudinal plane** and the **source aperture plane**

SEE: Figure 2

Note 1 to entry: If a transducer is circularly-symmetric, a radial line scan is sufficient to determine the width.

Note 2 to entry: If a HITU transducer has a hole in its centre, the beginning and ending −20 dB points of the width are measured and noted with reference to the centre.

Note 3 to entry: **Source aperture width** is expressed in metres (m).

[SOURCE: IEC 61828:~~2006~~2020, 3.136, modified – ~~two notes have been added~~ the reference to HITU transducers has been deleted in the Note 1 to entry.]

3.68
spatial-average pulse-average intensity
I_{sapa}
pulse-average intensity from one **ultrasonic transducer** or **ultrasonic transducer element group** averaged over the **beam-area** for that particular **ultrasonic transducer** or **ultrasonic transducer element group**

Note 1 to entry: A burst is also to be understood to be a pulse.

Note 2 to entry: **Spatial-average pulse-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.69
spatial-average temporal-average intensity
I_{sata}
~~equal to the~~ **temporal-average intensity** averaged over the **scan-area** or **beam area** as appropriate

Note 1 to entry: **Spatial-average temporal-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.70
spatial-peak pulse-average intensity
I_{sppa}
maximum value of the **pulse-average intensity** in an acoustic field or in a specified plane

Note 1 to entry: **Spatial-peak pulse-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.71
spatial-peak RMS acoustic pressure
p_{spr}
maximum value of the **RMS acoustic pressure** in an acoustic field or in a specified plane

Note 1 to entry: **Spatial-peak RMS acoustic pressure** is expressed in pascals (Pa).

3.72
spatial-peak temporal-average intensity
I_{spta}
maximum value of the **temporal-average intensity** in an acoustic field or in a specified plane

Note 1 to entry: For systems in **combined-operating mode**, the time interval over which the temporal average is taken is sufficient to include any period during which scanning ~~may~~ is not be taking place.

Note 2 to entry: **Spatial-peak temporal-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.73
spatial-peak temporal-peak acoustic pressure
p_{sptp}
larger of the **peak-compressional acoustic pressure** ~~or~~ and the **peak-rarefactional acoustic pressure**

Note 1 to entry: **Spatial-peak temporal-peak acoustic pressure** is expressed in pascals (Pa).

3.74
spatial-peak temporal-peak intensity
I_{sptp}
maximum value of the **temporal-peak intensity** in an acoustic field or in a specified plane

Note 1 to entry: **Spatial-peak temporal-peak intensity** is expressed in units of watt per metre squared (W/m^2).

3.75
temporal-average intensity
I_{ta}
time-average of the **instantaneous intensity** at a particular point in an acoustic field

Note 1 to entry: The time-average ~~should be taken~~ is considered over an integral number of **acoustic repetition periods**.

Note 2 to entry: ~~(Relating to ultrasonic medical diagnostic systems)~~ In principle, the **temporal-average intensity** is an average over a relatively long time interval. For ultrasonic medical diagnostic systems in **non-~~auto-~~scanning ~~systems~~ modes**, the **instantaneous intensity** ~~should be~~ is averaged over one or more **pulse repetition periods**. For ~~auto-~~ ultrasonic medical diagnostic systems in **scanning ~~systems~~ modes**, the **instantaneous intensity** ~~should be~~ is averaged over one or more **scan repetition periods** for a specified **operating mode**.

Note 3 to entry: **Temporal-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.76
temporal-peak acoustic pressure
p_{tp}
maximum value of the modulus of the **instantaneous acoustic pressure** at a particular point in an acoustic field

Note 1 to entry: **Temporal-peak acoustic pressure** is expressed in pascals (Pa).

3.77
temporal-peak intensity
I_{tp}
maximum value over time of the **instantaneous intensity** at a particular point in an acoustic field

Note 1 to entry: **Temporal-peak intensity** is expressed in units of watt per metre squared (W/m^2).

3.78
time-window-average intensity
$I_{\text{w},\Delta t/\text{s}}(t)$
time-varying value of the **instantaneous intensity** averaged over a window of duration Δt

$$I_{\text{w},\Delta t/\text{s}}(t) = \frac{1}{\Delta t} \int_{t-\Delta t/2}^{t+\Delta t/2} I(t')\,\mathrm{d}t' \tag{8}$$

where

$I(t)$ is the **instantaneous intensity**;

$\Delta t/\text{s}$ is the numerical value of the moving time window width in seconds;

t' is the variable of integration.

Note 1 to entry: The time varying **time-window-average intensity** for a time window width of 20 s, for instance, is denoted by $I_{\text{w},20}(t)$.

Note 2 to entry: **Time-window-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.79
transducer aperture area
A_{TA}
effective active area of an **ultrasonic transducer** in the **transducer aperture plane**

Note 1 to entry: **Transducer aperture area** is expressed in square metres (m^2).

[SOURCE: IEC 61828:2020, 3.145]

3.80
transducer aperture plane
plane that is orthogonal to the **beam axis** of the **unsteered beam**~~, or the axis of symmetry of the **azimuth plane** for an automatic scanner,~~ and is adjacent physically to the **ultrasonic transducer**

SEE: Figure 1

Note 1 to entry: If the **ultrasonic transducer** is flat, the plane is coplanar with the ~~radiating~~ transmitting surface of the **ultrasonic transducer**; if it is concave, the plane touches the periphery of the ~~radiating~~ transmitting surface; if it is convex, the plane is tangent to the centre of the ~~radiating~~ transmitting surface at the point of contact.

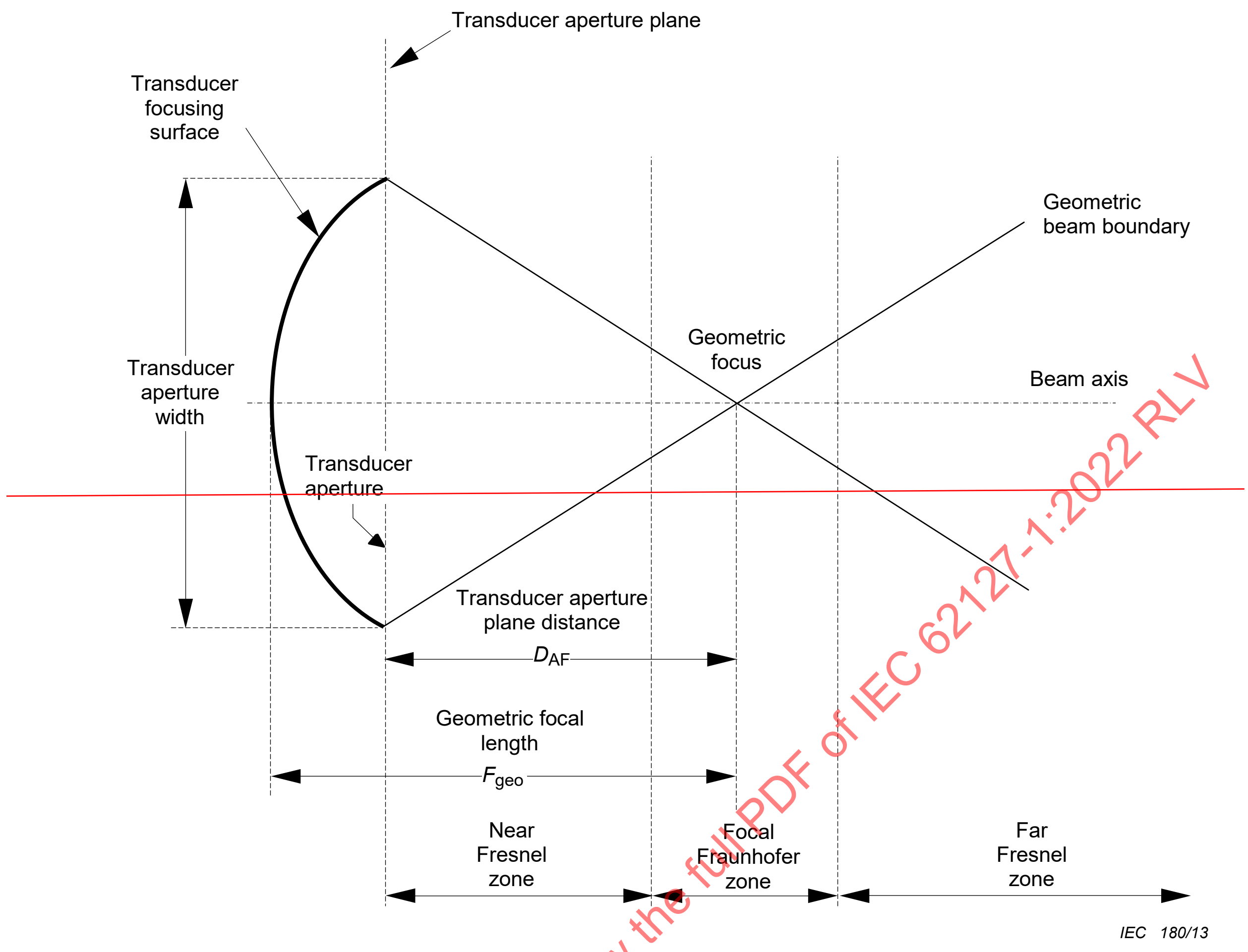
[SOURCE: IEC 61828:~~2001~~2020, 3.146]

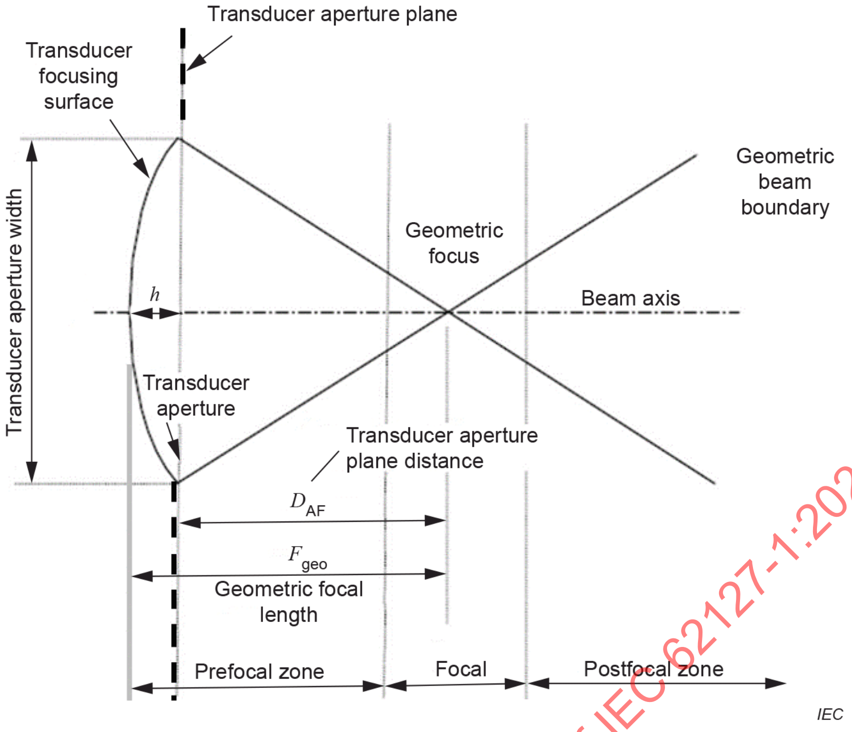
3.81
transducer aperture width
L_{TA}
full width of the transducer aperture along a specified axis orthogonal to the **beam axis** of the unsteered beam at the centre of the transducer

SEE: Figure 3

Note 1 to entry: **Transducer aperture width** is expressed in metres (m).

[SOURCE: IEC 61828:~~2006~~2020, 3.148, modified – ~~two notes have been added, and~~ The phrase "at the centre of the transducer" has been added to the definition.]


Transducer aperture plane
Transducer focusing surface
Geometric beam boundary
Geometric focus
Beam axis
Transducer aperture width
Transducer aperture
Transducer aperture plane distance
D_{AF}
Geometric focal length
F_{geo}
Near Fresnel zone
Focal Fraunhofer zone
Far Fresnel zone
IEC 180/13



The radius of curvature is $D = D_{AF} + h$.

[SOURCE: IEC 61828:2020]

Figure 3 – Parameters for describing an example of a focusing transducer of known geometry

3.82
transducer assembly
those set of parts of **medical diagnostic ultrasonic equipment** comprising the **ultrasonic transducer** and/or **ultrasonic transducer element group**, together with any integral components, such as an acoustic lens or integral stand-off

Note 1 to entry: The **transducer assembly** is usually separable from the **ultrasound instrument console**.

3.83
transition distance
z_T
for a given **longitudinal plane**, the **transition distance** is defined based on the transducer design (when known) or from measurement:

a) from design: the **transition distance** is the equivalent area of the ultrasonic **transducer aperture width** divided by π times the **effective wavelength**, λ;

b) for measurements, the **transition distance** is the equivalent area of the **source aperture width** divided by π times the **effective wavelength**.

NOTE 1 Using method a), an unapodized **ultrasonic transducer** with circular symmetry about the **beam axis,** the equivalent area is πa^2, where a is the radius. Therefore the **transition distance** is $z_T = a^2/\lambda$. For the first example of a square **ultrasonic transducer,** the equivalent area is $(L_{TA})^2$, where L_{TA} is the **transducer aperture width** in the **longitudinal plane**. Therefore, the **transition distance** for both orthogonal **longitudinal planes** containing the sides or **transducer aperture widths**, is $z_T = (L_{TA})^2 /(\pi\lambda)$. For the second example, for a rectangular **ultrasonic transducer** with **transducer aperture widths** L_{TA1} and L_{TA2}, the equivalent area for the first linear transducer aperture width for the purpose of calculating the **transition distance** for the associated **longitudinal plane** is $(L_{TA1})^2$, where L_{TA1} is the **transducer aperture width** in this **longitudinal plane**. Therefore, the **transition distance** for this plane is $z_{T1} = (L_{TA1})^2 /(\pi\lambda)$. For the orthogonal **longitudinal plane** that contains the other **transducer aperture width**, L_{TA2}, the equivalent area for the other for the purpose of calculating the transition distance for the

~~associated **longitudinal plane** is $(L_{TA2})^2$, where L_{TA2} is the **transducer aperture width** in this **longitudinal plane**. Therefore, the **transition distance** for this plane is $z_{T2} = (L_{TA2})^2 / (\pi\lambda)$.~~

~~NOTE 2 Using method b) for measurements in a longitudinal plane, the **source aperture width**, L_{SA}, in the same plane is used in $z_T = (L_{SA})^2 / (\pi\lambda)$.~~

~~NOTE 3 **Transition distance** is expressed in metre (m).~~

~~[SOURCE: IEC 61828:2006, definition 4.2.75, modified – there is significant difference in the layout and content of the definition]~~

aperture area divided by π times the effective wavelength λ

[SOURCE: IEC 61828:2020, 3.153, modified – The words "effective wavelength" have been added to the definition.]

3.83.1
transition distance for design

z_{TD}

<for a given **longitudinal plane**> **transducer aperture area** A_{TA} of the **ultrasonic transducer** divided by π times the effective wavelength λ

$$z_{TD} = A_{TA}/(\pi\lambda) \tag{9}$$

Note 1 to entry: For design, for an unapodized **ultrasonic transducer** with circular symmetry about the **beam axis**, the **source aperture area** is πa_e^2, where a_e is the effective radius; therefore the **transition distance** is $z_T = a_e^2/\lambda$.

Note 2 to entry: For a spherically focusing transducer, the **transition distance** is approximately the same but more exactly it is $z_T = 2D^2\left(1-\sqrt{1-(a/D)^2}\right)\Big/\lambda$, where D is the radius of curvature.

Note 3 to entry: For design, for an unapodized rectangular **ultrasonic transducer** which has a **transducer aperture width**, L_{TA1}, in a specified **longitudinal plane**, the effective in-plane area is $(L_{TA1})^2$. Therefore, for this plane, the **transition distance** is $z_{T1} = (L_{TA1})^2/(\pi\lambda)$. The **transition distance** for the orthogonal **longitudinal plane** including the second **transducer aperture width** is $z_{T2} = (L_{TA2})^2/(\pi\lambda)$.

Note 4 to entry: For apodized transducers with a symmetric even apodization or weighting function W (normalized to a maximum value of one for the particle velocity distribution), the **transition distances** are the following.

For circularly symmetric transducers with an active radius a:

$$z_T = \left(\frac{2}{\lambda}\right)\int_0^a W(r)r\,\mathrm{d}r$$

For a rectangular transducer with a physical aperture length L in a given longitudinal plane, for example, xz:

$$z_T = \left(\frac{4}{\pi\lambda}\right)\left|\int_0^{L/2} W(x)\,\mathrm{d}x\right|^2$$

Note 5 to entry: For symmetric shapes other than the most common cases of circular symmetry and rectangular geometry, the same definition of **transition distance** can be used. For example, for apertures with n-fold symmetry ($n > 2$) such as hexagons and octagons, the **transition distance** in a symmetry plane perpendicular to a side is equal to the area of the aperture divided by $(\pi\lambda)$. For annular arrays with several rings, the equivalent area is the total (all rings) area of the active aperture. For cases in which unique phasing is used, such as annular arrays with alternate phase shifts (0° or 180°) in addition to intended focusing or for cases of apertures with unusual shapes and phasing, three-dimensional diffraction computation is employed to determine the minimum beamwidth corresponding to the appropriate **transition distance**.

Note 6 to entry: **Transition distance for design** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.153.1, modified – Note 6 to entry has been omitted here.]

3.83.2
transition distance for measurement
z_{TM}
<for a given **longitudinal plane**> **source aperture area**, A_{SAeff}, of the **ultrasonic transducer** divided by π times the effective wavelength λ

$$z_{TM} = A_{SAeff}/(\pi\lambda) \tag{10}$$

Note 1 to entry: For measurements in each specified **longitudinal plane**, the **source aperture width** in that plane is used, or $z_{T1} = (L_{SA1})^2/(\pi\lambda)$; in the other orthogonal plane, $z_{T2} = (L_{SA2})^2/(\pi\lambda)$.

Note 2 to entry: **Transition distance for measurement** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.153.2]

3.84
treatment head
assembly comprising an **ultrasonic transducer** and associated parts for local application of **ultrasound** to the patient

[SOURCE: IEC 60601-2-5:2009, 201.3.214, modified – A note in the original has been deleted.]

3.85
ultrasound instrument console
electronic unit to which the **transducer assembly** is attached

3.86
ultrasonic scan line
<for scanning systems> **beam axis** for a particular **ultrasonic transducer element group**, or for a particular excitation of an **ultrasonic transducer** or **ultrasonic transducer element** group

Note 1 to entry: In this document, **ultrasonic scan line** refers to the path of acoustic pulses and not to a line on an image on the display screen of a system.

Note 2 to entry: In general, this document assumes that an individual scan line repeats exactly after a given number of acoustic pulses. In case an **ultrasonic transducer** or **ultrasonic transducer element group** radiates ultrasound without any sequence of repetition, it will not be possible to characterize a scanned mode in the way described in this document. The approach described in Annex F can be useful when synchronization cannot be achieved.

Note 3 to entry: The case where a single excitation produces ultrasonic beams propagating along more than one **beam axis** is not considered.

3.87
ultrasonic scan line separation
s_s
<for automatic scanning systems> distance between the points of intersection of two consecutive **ultrasonic scan lines** of the same type and a specified line in the **scan plane**

Note 1 to entry: For this definition it is assumed that consecutive **ultrasonic scan lines** are spatially adjacent; this is not true for all types of scanning equipment.

Note 2 to entry: The **ultrasonic scan line separation** is expressed in metres (m).

3.88
ultrasonic transducer
device capable of converting electrical energy to mechanical energy within the ultrasonic frequency range and/or reciprocally of converting mechanical energy to electrical energy

3.89
ultrasonic transducer element
element of an **ultrasonic transducer** that is excited in order to produce an acoustic signal

3.90
ultrasonic transducer element group
group of elements of an **ultrasonic transducer** which are excited together in order to produce an acoustic signal

3.91
ultrasonic transducer element group dimensions
dimensions of the surface of the group of elements of an **ultrasonic transducer element group** which includes the distance between the elements, hence representing the overall dimensions

Note 1 to entry: **Ultrasonic transducer element group dimensions** are expressed in metres (m).

3.92
uncertainty
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

Note 1 to entry: See ISO/IEC Guide 98-3:2008, 2.2.3.

4 Symbols

a_{h}	**effective hydrophone** ~~radius~~ **size**
a_{g}	**hydrophone geometrical radius**
a_{t}	effective radius of a non-focusing **ultrasonic transducer**
~~a_{h3}, a_{h6}~~	~~effective radii of the active element of a hydrophone, determined from directional response measurements, at the −3 dB and −6 dB levels~~
a_{max}	maximum effective radius for a specific **hydrophone** application
arp	**acoustic repetition period**
$A_{\mathrm{b,6}}$, $A_{\mathrm{b,20}}$	**beam area** corresponding to −6 dB **beam area** and −20 dB **beam area**
A_{g}	geometrical area of an **ultrasonic transducer**
A_{ob}	**output beam area**
A_{s}	**scan-area**
A_{SAeff}	**source aperture area**
A_{TA}	**transducer aperture area**
BW	**bandwidth**
c	speed of sound in the medium (usually water)
C	end-of-cable capacitance of a **hydrophone**
C_{el}	parallel input capacitance of an electrical load
d_{offset}	**offset distance**
f_{awf}	**acoustic frequency**, **acoustic-working frequency**
f_{p}	**peak pulse** acoustic frequency
f_{t}	time average **acoustic frequency**
F_{a}	**local area factor**

~~F_g 0,69 · A_g/(–6 dB beam area)~~

I	**instantaneous intensity**
I_{ob}	**output beam intensity**
I_{pa}	**pulse-average intensity**
I_{sapa}	**spatial-average pulse-average intensity**
I_{sata}	**spatial-average temporal-average intensity**
I_{sppa}	**spatial-peak pulse-average intensity**
I_{ta}	**temporal-average intensity**
I_{tp}	**temporal-peak intensity**
I_{spta}	**spatial-peak temporal-average intensity**
I_{sptp}	**spatial-peak temporal-peak intensity**
$I_{w,\Delta t/s}$	**time-window-average intensity**
k	$2\pi/\lambda$
K_{sa}	spatial averaging correction factor
$L_{M_L}(f)$	**end-of-cable loaded sensitivity level**
$L_p(f)$	pressure level spectrum
$LP(f)$	low-pass filtering function
L_{TA}	**transducer aperture width**
L_{SA}	**source aperture width**
$M_c(f)$	**end-of-cable open-circuit sensitivity**
$M_L(f)$	**end-of-cable loaded sensitivity**
n_{pps}	**number of pulses per ultrasonic scan line**
n_{sl}	**number of ultrasonic scan lines** per image for spatial distribution
p	**instantaneous acoustic pressure**
pii	**pulse-intensity integral**
$ppsi$	**pulse-pressure-squared integral**
p_m	**mean peak acoustic pressure**
p_{tp}	**temporal-peak acoustic pressure**
prr	**pulse repetition rate**
prp	**pulse repetition period**
p_{spr}	**spatial-peak RMS acoustic pressure**
p_{sptp}	**spatial-peak temporal-peak acoustic pressure**
p_{RMS}	**RMS acoustic pressure**
p_c (p_+)	**peak-compressional acoustic pressure**
p_r (p_-)	**peak-rarefactional acoustic pressure**
P	total ultrasonic power
P_{beam}	total power emitted by one acoustic scan line
R_{bh}	ratio of the −6 dB beamwidth to the effective **hydrophone** diameter

s_s	**ultrasonic scan line separation**
srp	**scan repetition period**
srr	**scan repetition rate**
t_d	**pulse duration**
$\underline{U}_L(f)$	end-of-cable voltage for a **hydrophone**
v	instantaneous particle velocity
w_6, w_{12}, w_{20}	**beamwidth** (at −6 dB and −12 dB and −20 dB levels)
X_{ob}, Y_{ob}	**output beam dimensions**
z	distance between a **hydrophone** and an **ultrasonic transducer**
z_c	**distance** z_c
z_{offset}	distance z_{offset}
z_{ppsi}	**distance** z_{ppsi}
z_r	**distance** z_r
z_{spta}	**distance** z_{spta}
z_T	**transition distance**
z_{TD}	**transition distance for design**
z_{TM}	**transition distance for measurement**
$\underline{Z}_h$	complex electric output impedance of a **hydrophone** or **hydrophone assembly**
$\underline{Z}_L$	**electric load impedance**
β	nonlinearity parameter
θ	angle of incidence of an ultrasonic wave with respect to the **hydrophone** axis, (θ_3, θ_6: with special reference to 3 dB and 6 dB defined levels)
λ	acoustic wavelength in a liquid
ρ	density of the medium (usually water)
σ_q	**local distortion parameter**
ω	($2\pi f_{awf}$) circular frequency

5 Measurement requirements

5.1 Requirements for hydrophones and amplifiers

5.1.1 Introduction Preface

In order to select a **hydrophone** and amplifier that is appropriate for the type of measurement to be undertaken, it shall be ensured that the selected devices comply conform with the following requirements. Requirements for **hydrophone** performance in this clause are either in addition to or supersede those for **hydrophones** in IEC 62127-3.

5.1.2 General

It is assumed throughout this document that a **hydrophone** is a device that responds to waterborne acoustic waves [see IEV 801-32-26] in such a way that the output voltage is proportional to the acoustic pressure. Generally, this relationship is frequency dependent; thus, if $\underline{M}_L(f)$ is the **end-of-cable loaded sensitivity** of a **hydrophone** (see 3.25 and Annex C), the **instantaneous acoustic pressure** $p(t)$ is related to the measured end-of-cable voltage $u_L(t)$ by

~~$p(t) = \Im^{-1}[\underline{U}_L(f) / \underline{M}_L(f)]$~~ $$p(t) = \mathcal{F}^{-1}[\underline{U}_L(f) / \underline{M}_L(f)] \qquad (11)$$

where

$\mathcal{F}^{-1}$ denotes the inverse Fourier transform;

~~$U_L(f)$~~ $\underline{U}_L(f)$ is the Fourier transform result of $u_L(t)$.

NOTE 1 See 5.1.7.2 and Annex D to implement this method.

NOTE 2 For mathematical completeness, Formula (11) needs to include the real part operator, Re, on the right-hand side. However, for the type of spectra relevant here, the time domain data is not likely to comprise imaginary components with the exemption of a possible constant numerical residue, and thus Re is omitted in this formula throughout the document.

If the **hydrophone** or **hydrophone assembly** meets the requirements of a narrow-band approximation as specified in 5.1.7.1, then **instantaneous acoustic pressure** can be determined from Formula (12):

~~$p(t) = u_L(t) / M_L(f_{awf})$~~ $$p(t) = u_L(t) / |\underline{M}_L(f_{awf})| \qquad (12)$$

where

~~$M_L(f_{awf})$~~ $|\underline{M}_L(f_{awf})|$ is the modulus of the **end-of-cable loaded sensitivity** of the **hydrophone** at the **acoustic-working frequency**.

5.1.3 Sensitivity of a hydrophone

When no **hydrophone pre-amplifier** is used, the sensitivity of the **hydrophone** shall refer to the **end-of-cable loaded sensitivity** and shall be determined for the particular electrical loading conditions (see 3.22).

When a **hydrophone pre-amplifier** is used, the sensitivity of the **hydrophone** shall refer to the **end-of-cable loaded sensitivity** which relates to the particular **hydrophone assembly**.

NOTE 1 The method outlined in IEC 62127-3 ~~may~~ can be used for the determination of **end-of-cable loaded sensitivity** assuming the **end-of-cable open-circuit sensitivity of the hydrophone** is known.

NOTE 2 See Clause B.10 for tabulated examples of specification parameters.

5.1.4 Directional response of a hydrophone

The directional response of the **hydrophone** shall be known.

Symmetry of the directional response shall conform to IEC 62127-3.

NOTE There are two reasons to know the directional response of a **hydrophone**. First, it ~~may~~ can be necessary as part of the field characterization procedures described in Annex B, in which case the directional response ~~should~~ needs to be known at the appropriate **acoustic-working frequency**. Secondly, the directional response is used to derive the **effective hydrophone** ~~**radius**~~ **size**.

5.1.5 Effective hydrophone ~~radius~~ size

The **effective hydrophone** ~~**radius**~~ **size** shall be known and determined following the method described in IEC 62127-3.

5.1.6 Choice of the size of a hydrophone active element

5.1.6.1 General

The choice of the **effective hydrophone** ~~**radius**~~ **size** for a specific application shall be determined by consideration of the following.

The effective ~~radius~~ size of the element should ideally be comparable with or smaller than one quarter of the acoustic wavelength, so that phase and amplitude variations do not contribute significantly to measurement **uncertainties**.

It is not possible, because of the large range of types of **ultrasonic transducers**, to establish a simple relationship between the optimum effective element size of the **hydrophone** and parameters such as the **ultrasonic transducer** dimension, the acoustic wavelength and the distance from the **ultrasonic transducer**. However, in the **far field** it is reasonable to relax the above criterion. For circular **ultrasonic transducers**, the following criterion may be used as a guide to the determination of the maximum effective radius a_{max} of a **hydrophone** active element. a_{max} is given by Formula (13):

$$a_{max} = \frac{\lambda}{8a_1}\left(l^2 + a_1^2\right)^{1/2} \quad (13)$$

where

a_1 is the effective radius of the **ultrasonic transducer**;

l is the distance between the **hydrophone** and the **ultrasonic transducer** face;

λ is the acoustic wavelength corresponding to the **acoustic-working frequency**.

See [2] [1] and [3].

For a focused **ultrasonic transducer**, the above relationship may still be used.

For an **ultrasonic transducer** with a non-circular element, the above relationship may still be used by replacing a_1 by one half the maximum **ultrasonic transducer dimension** or **ultrasonic transducer element group dimension**.

Requirements of the size of the **hydrophone** active element are relaxed for measurements of ultrasonic fields generated by physiotherapy systems (see 8.3.1).

For representative experimental data, see [1].

5.1.6.2 Spatial averaging effect

The practical requirement of an adequate signal-to-noise ratio or other considerations can lead to the use of a **hydrophone** with an element size greater than that recommended above. In this case, care should be taken in interpreting measurements as a piezoelectric **hydrophone** is a phase sensitive detector that integrates the complex acoustic pressure over its active element.

When the **hydrophone** is translated from the position of maximum received signal in any direction normal to the **beam axis** by an amount equal to the **effective hydrophone** ~~**radius**~~ **size** element, the decrease in signal should be less than 1 dB. If this is not the case, corrections for spatial averaging should be made. See Annex E.

1 Numbers in square brackets refer to the Bibliography.

Improved corrections can also be made using diffraction corrections, see [2], [3], [4], [5].

The spatial averaging effect may also be addressed by spatial deconvolution of the **hydrophone** aperture as proposed in [6], [7], [8]. However, the method may suffer from signal-to-noise ratio issues in practical cases.

For nonlinear broadband **acoustic pulse waveforms**, the method of inverse spectral filtering as outlined in Clause E.2 should be applied to correct for spatial averaging.

5.1.7 Bandwidth

5.1.7.1 Narrow-band approximation

Narrow-band approximations shall be considered as being appropriate whenever the **local distortion parameter** is less than 0,5 (see 7.2.4).

In this case, it is sufficient to consider the sensitivity value at the **acoustic-working frequency** as being representative of the sensitivity value at all frequencies of interest.

NOTE 1 When measuring narrow-band acoustic signals, it is assumed that all the significant frequency components within the signal are located at frequencies close to the **acoustic-working frequency**. In this case, there will be little variation in the **end-of-cable loaded sensitivity** of the **hydrophone**.

NOTE 2 The simplifying assumption given above can also be used when measuring acoustic fields with a broader frequency content provided that the **end-of-cable loaded sensitivity** of the **hydrophone** shows only limited variations over the frequency range necessary to accurately represent the acoustic signal.

If the value of the **local distortion parameter** exceeds 0,5 (see 7.2.4), then the **end-of-cable loaded sensitivity level** of the **hydrophone** or **hydrophone assembly** shall vary by less than ±3 dB over the frequency range (f) from one octave below to ~~the lesser of~~ three octaves above the **acoustic-working frequency** ~~or 40 MHz~~, where the 0 dB reference point is located at the **acoustic-working frequency**, f_{awf}. That is, for

~~$f_{awf}/2 \le f \le \min\{8f_{awf}, 40\ \text{MHz}\}$~~

~~$M_{L,dB}(f_{awf}) - 3\ \text{dB} \le M_{L,dB}(f) \le M_{L,dB}(f_{awf}) + 3\ \text{dB}$~~

~~where~~ $M_{L,dB}(f) = 20\log_{10}\dfrac{M_L(f)}{M_0}$ ~~dB and~~ $M_0 = 1\dfrac{\text{V}}{\text{Pa}}$

~~NOTE 3 There is scientific justification for an upper limit of 8 times f_{awf}, but 40 MHz is inserted here due to the current limit in the hydrophone calibration standard IEC 62127-2. If possible, recommendations based on [6] and [7], specifically $f_{awf}/16 \le f \le 8f_{awf}$, (i.e. 4 octaves below to 3 octaves above f_{awf}), should be followed (see also [] and [] and Annex A).~~

~~If the narrow-band approximation cannot be followed the broadband measurements in 5.1.7.2 should be followed.~~

$$f_{awf}/2 \le f \le 8f_{awf} \quad (14)$$

$$L_{M_L}(f_{awf}) - 3\ \text{dB} \le L_{M_L}(f) \le L_{M_L}(f_{awf}) + 3\ \text{dB} \quad (15)$$

where $L_{M_L}(f) = 20\log_{10}\dfrac{|M_L(f)|}{M_{ref}}\text{dB}$ and $M_{ref} = 1\dfrac{\text{V}}{\text{Pa}}$.

NOTE 3 There is scientific justification for using an extended range $f_{awf}/16 \leq f \leq 8f_{awf}$ (i.e. four octaves below to three octaves above f_{awf}), based on [9] and [10] (see also Annex A). However, experimentally determined **hydrophone** calibration data is available for a limited **bandwidth** only, for instance from 1 MHz to 100 MHz. To judge whether the narrow-band approximation is appropriate according to Formulas (14) and (15), **hydrophone** frequency response extrapolation can be applied as an alternative method in the same way as described in 5.1.7.2.2 including Notes 1, 2 and 3, and Annex D for broadband measurements, if necessary. That is, extrapolation of $\underline{M}_L(f)$ can be used to cover frequencies f outside the calibration range available, at maximum below half of the **acoustic-working frequency** towards zero and above the lesser of four times the **acoustic-working frequency** or 100 MHz towards the Nyquist frequency $f_{Nyquist}$, e.g. for $0 \leq f < f_{awf}/2$ and for min [4 f_{awf}, 100 MHz] $< f \leq f_{Nyquist}$. Details on considerations for appropriate extrapolation are provided in D.4.2.

If the narrow-band approximation requirements are not fulfilled the broadband measurement method of 5.1.7.2 shall be followed.

If the broadband measurement method of 5.1.7.2 is implemented in the measurement system, it may be used for all situations including those covered by the narrow-band approximation requirements.

Measurements performed in conformity with the first edition of IEC 62127-1 may have considered frequency contributions up to 40 MHz only. The changed requirements of this second edition do not imply that such measurements of the past shall be repeated for output measurements on equipment already characterized in conformity with the first edition. If necessary, the systematic error of the limited bandwidth may in such cases then be attributed by an additional **uncertainty** contribution.

NOTE 4 See 8.2.4 for specific consideration of diagnostic equipment of low acoustic output.

5.1.7.2 Broadband measurements

5.1.7.2.1 General

~~In case the narrow-band approximation requirements cannot be met and the uncertainty in the measurement becomes unacceptably large due to limited bandwidth of the hydrophone, corrections should be made using the frequency-dependent sensitivity of the hydrophone and the frequency content of the ultrasonic pulse waveform. If the requirements for the deconvolution method are satisfied, the methods given in Annex D may produce more accurate results.~~

In case the narrow-band approximation requirements cannot be met, the **uncertainty** in the measurement can become unacceptably large due to limited bandwidth and frequency dependent sensitivity variation of the **hydrophone.** Voltage-to-pressure conversion shall then be performed using the frequency-dependent sensitivity of the **hydrophone** and the frequency content of the **acoustic pulse waveform**. The measurement method based on deconvolution of the acquired waveform with the **hydrophone** response as described here in 5.1.7.2 and in Annex D produces more accurate results. For performing deconvolution, specific aspects of hydrophone calibration data conditioning, regularization filtering of signal spectra, and **uncertainty** determination shall be considered in accordance with 5.1.7.2.2, 5.1.7.2.3 and 5.1.7.2.4.

5.1.7.2.2 Deconvolution bandwidth

Application of Formula (11) to determine the **acoustic pulse waveform** requires the complex division of the voltage spectrum $\underline{U}_L(f)$ by the sensitivity $\underline{M}_L(f)$. For this operation data sets must match, e.g. the frequency increment and range of both spectra must be the same. The frequency increment of $\underline{U}_L(f)$ depends on the length of the acquired **acoustic pulse waveform** (including zero padding if applicable) and the frequency range extends from 0 to the Nyquist frequency associated with the sample rate used. Experimentally obtained **hydrophone** calibration data $\underline{M}_L(f)$, however, may provide different frequency increments and ranges. If necessary, calibration data can be interpolated between consecutive sensitivity data points available for the **hydrophone** (see Annex D). If necessary, extrapolation of $\underline{M}_L(f)$ may be used to cover frequencies f outside the calibration range available, at maximum below half of the **acoustic-**

working frequency towards zero and above the lesser of four times the **acoustic-working frequency** or 100 MHz towards the Nyquist frequency $f_{Nyquist}$, e.g. for $0 \le f < f_{awf}/2$ and for min $[4\,f_{awf}$, 100 MHz$] < f \le f_{Nyquist}$. Details on considerations for appropriate extrapolation are provided in D.4.2.

NOTE 1 The maximum lower limit of 100 MHz for extrapolating at higher frequencies in the above requirement assumes availability of hydrophone calibration certificates up to 100 MHz at the time this document is published. If only a lower upper limit is available at this time, then that limit can be used instead for practicability.

NOTE 2 Secondary pulse calibration techniques have been developed [11], [12] and can be applied by the hydrophone user to determine the sensitivity of the individual hydrophone in frequency ranges where calibration service is not available. The same techniques can be used, in general, for hydrophone calibration data extrapolation, and to check conformity with the narrow-band approximation through Formulas (14) and(15).

NOTE 3 For some types of hydrophones, the variation of sensitivity at higher frequency can possibly be predicted from calibration data obtained at lower frequencies. For example, above the resonance frequency of a membrane hydrophone, the sensitivity is likely to follow a predictable trend. In such cases, the sensitivity prediction can be used in place of direct measurements so long as the **uncertainty** in the prediction is accounted for, based on calibration measurements of similar hydrophones throughout the frequency range where the prediction is used.

5.1.7.2.3 Regularization

Deconvolution is mathematically speaking an ill-posed inverse problem, which in the discrete time domain results in an ill-conditioned estimation problem [13], [14]. For instance, at very high frequency the acquired **hydrophone** signal may still comprise some noise contribution but the sensitivity may be close to zero. Formula (11) then leads to a large impact of such noise within the deconvolution, see Annex D for a waveform example. To obtain waveforms with acceptable overall noise, in general, appropriate low-pass filtering is necessary; this also reduces the occurrence of Gibbs oscillations. Including such a regularization, Formula (11) is then extended towards

$$p(t) = \mathcal{F}^{-1}\left(\underline{LP}(f) \cdot \frac{\underline{U}_{\mathrm{L}}(f)}{\underline{M}_{\mathrm{L}}(f)} \right) \qquad (16)$$

where $\underline{LP}(f)$ denotes the complex-valued low-pass filtering function. Different filter functions can be used for **hydrophone** signal deconvolution [14], [15], [16], [17], [18], [19], [20], [21]. Since any low-pass filtering induces additional **bandwidth** limitation and hence possibly cutting of peak pressure parts of the waveform, the filter cut-off frequency shall be kept as large as possible while still providing enough noise suppression to achieve reasonable **uncertainties** for waveform parameters. The −3 dB cut-off frequency of the low-pass filtering shall be 8-times the **acoustic-working frequency** f_{awf} determined from the pressure spectrum without low-pass filtering or higher.

NOTE 1 In measurement situations with stable pulse repetition, high-frequency noise suppression can be improved by increasing signal averaging.

NOTE 2 In general, **bandwidth** reduction of nonlinearly distorted ultrasonic waveforms through additional low-pass filtering will affect the peak compressional pressure stronger than the peak rarefactional pressure and derived intensity data.

NOTE 3 For high amplitude nonlinearly distorted waveforms of high intensity therapeutic ultrasound or lithotripsy comprising up to 100 harmonics, cut-off frequencies larger than 8-times the **acoustic-working frequency** are needed to avoid cutting of the peak compressional waveform parts and excessive systematic **uncertainty** contribution of the regularization. Specifications are provided in 8.3.2.

NOTE 4 A good choice for the numerical filter type sufficient in many applications is of the form $\underline{LP}(f) = 1 \Big/ \left(1 + \frac{i f}{f_{\mathrm{g}}}\right)^2$ with $i = \sqrt{-1}$ and f_{g} denoting the −6 dB corner frequency. The −3 dB corner frequency then is approximately f_{g} /1,555 [17].

NOTE 5 In principle, the regularization filter and cut-off frequency choice can be supported by optimizing the overall **uncertainty** of the deconvolved waveform including the partly competing noise and regularization components [14].

NOTE 6 Of the acoustic parameters listed in 7.2.1, the **peak compressional acoustic pressure** is most likely to be affected by the choice of the regularization filter.

5.1.7.2.4 Uncertainty estimation for broadband measurement method

Due to the application of Fourier transforms and inverse Fourier transforms, regularization filtering, as well as complex-valued **hydrophone** calibration data, the **uncertainty** estimation for the broadband measurement method may appear less straightforward than in other situations. However, a GUM-compliant **uncertainty** evaluation (ISO/IEC Guide 98-3 and ISO/IEC Guide 98-3/Suppl.2 [22]) can be performed utilizing closed formulae for the propagation of **uncertainties** when discrete Fourier and inverse Fourier transforms are applied, and an open-source software tool GUM2DFT[2] is available [21]. The method enables, for instance, to propagate to the time domain the frequency dependent **uncertainties** of the **hydrophone** calibration data provided for modulus and phase in the frequency domain.

The introduction of additional numerical low-pass filtering for regularizing the deconvolution problem introduces an additional **uncertainty** contribution to the measurement and data evaluation procedure. The impact of the induced systematic error can be quantitatively assessed, for instance, by considering a continuous upper bound function in the frequency domain for the pressure magnitude spectrum based on a simple one-parametric basis functions approach and incorporating additional prior knowledge, like monotonously decreasing spectral components with frequency expected for nonlinearly distorted **acoustic pulse waveforms**, and typical signature of high frequency noise in distinction to waveform signal contribution [14].

5.1.8 Linearity

The linear response, as defined in IEC 62127-3, should extend to 5 MPa.

The upper limit of known dynamic range shall be stated, in particular if below 5 MPa.

5.1.9 Hydrophone signal amplifier

5.1.9.1 General

Hydrophone amplifiers shall meet the following performance requirements.

5.1.9.2 Requirements for all amplifiers

The amplifier gain shall allow the **hydrophone assembly** to meet the requirements given in 5.1.7.

The sensitivity level shall not vary by more than 0,5 dB per 100 kHz frequency increment inside the stated **bandwidth**. The requirement can be verified using an appropriate representation of the frequency response that resolves all important details of the frequency dependence.

The linearity with input signal over a dynamic range of 50 dB shall be ±0,3 dB.

The spectral noise measured generated by the **hydrophone assembly** shall be sufficiently low to allow measurements to be performed with an adequate signal-to-noise ratio for any frequency within the **bandwidth** considered.

The following performance parameters shall be specified:

2 This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

– the gain as a function of frequency;
– the input impedance as a function of frequency, either the real and imaginary components ($\underline{Z}_L$) (see 3.22), or the equivalent parallel resistive and capacitive components;
– the output impedance.

5.1.9.3 Additional requirements for differential amplifiers

The impedance requirements given above shall apply except that the impedance is measured between the two active inputs.

The common mode rejection shall be at least 40 dB (referred to the input) over the frequency range one octave below to two octaves above f_{awf}. See [23], [24].

5.1.10 Hydrophone cable length and amplifiers

A connecting cable of a length and characteristic impedance which ensures that electrical resonance in the connecting cable does not affect the defined **bandwidth** of the **hydrophone** or **hydrophone assembly** shall be chosen. The cable shall also be terminated appropriately.

To minimize the effect of resonance in the connecting cable, the length of the **hydrophone** cable (in metres) shall be much less than $50/(f_{awf} + BW_{20})$, where f_{awf} is the **acoustic-working frequency** in MHz and BW_{20} is the −20 dB **bandwidth** in MHz of the **hydrophone** signal. In most cases a cable length of ≤ 15 cm ~~should be~~ is usually adequate (see [25]).

NOTE 1 Attention ~~should~~ is to be paid to the appropriateness of the output impedance of the **hydrophone**/amplifier in relation to the input impedance of the connected measuring device.

NOTE 2 Methods that ~~may~~ can be used to correct the effects of finite **bandwidth** of the **hydrophone**/amplifier on waveforms suffering distortion from nonlinear propagation are given in Annex D.

5.2 Requirements for positioning and water baths

5.2.1 General

There are various possible systems that may be used to mount the **ultrasonic transducer** and **hydrophone**. The general performance requirements for such systems are specified here, and these are considered as optimum for the purposes of this document. Alternative positioning systems may be used providing equivalence with those described in this subclause is demonstrated.

Annex J shows a simple configuration of tank, **ultrasonic transducer** and **hydrophone** intended to show only the coordinate axes and degrees of freedom referred to in this document.

5.2.2 Positioning systems

5.2.2.1 Transducer positioning

The **ultrasonic transducer** under test shall be supported using a positioning system such that its face is fully immersed in the water bath and at a distance from any adjacent surface, for instance, a water/air interface, so that reflected ultrasound from this surface does not interfere with the main received signal. For the situation when the surface is parallel to the **beam axis**, the following criteria shall be satisfied.

If z is the distance between the active element of a **hydrophone** and the face of an **ultrasonic transducer** and t is the time between the arrival of the direct pulse at the **hydrophone** and the end of the measurement acquisition period, then the minimum distance, h, between the **beam axis** and the reflecting surface shall be determined from Formula (17):

$$(z^2 + 4h^2)^{1/2} - z > c\,t \tag{17}$$

It is preferable to immerse the transducer and not to use a membrane between the face of the **ultrasonic transducer** and the water bath. If, however, a membrane is needed, then the membrane should be as thin as practicable and should be kept as close to the front surface of the **ultrasonic transducer** as is possible. Close acoustic coupling should be ensured by using a water-based coupling agent, taking care to exclude bubbles of air. Measurements of acoustic parameters should be corrected for transmission loss of the membrane.

5.2.2.2 Hydrophone positioning

The **hydrophone** shall be set up in the coordinate positioning system such that the direction of maximum sensitivity of the **hydrophone** is approximately parallel to the anticipated direction of the **beam axis** of the **ultrasonic transducer** to be measured.

NOTE To avoid effects on the measurements made on continuous wave fields due to reflection of ultrasound from the surface of membrane **hydrophones**, the **hydrophone** ~~may~~ can be tilted. Tilting ensures that the reflected ultrasound either does not interfere significantly with the transducer or is not subsequently reflected from the transducer face, producing interference effects. Two methods used to determine the rotation required are described in Annex B.

5.2.2.3 Spatial positioning

The **hydrophone** and/or the **ultrasonic transducer** shall be supported from a positioning system to allow them to be positioned relative to each other at any desired point within a space with the following degrees of freedom:

a) spatial positioning along three orthogonal axes (named x, y and z), one (designated the z-axis) being the **beam axis** of the active element of the **ultrasonic transducer**;

b) to be able to reproduce positions, all translation and rotation systems should be provided with position indicators;

c) the repeatability of positioning should be 0,10λ or 0,05 mm, whichever is smaller.

NOTE 1 After alignment, the z-axis ~~should~~ is expected to be parallel to the **beam axis** of the **ultrasonic transducer**.

NOTE 2 It is possible to relax the requirement of the reproducibility for many measurements. A reasonable basis is to relate the precision of the positioning system to the diameter of the active element of the **hydrophone**. In the direction perpendicular to the direction of propagation of the ultrasound, a precision equivalent to 10 % of the diameter of the active element of the **hydrophone** is usually adequate, while in a direction parallel to the propagation direction a precision equivalent to the diameter of the active element is usually adequate.

5.2.3 Water bath

5.2.3.1 General

The size of the measurement vessel shall be such that the **ultrasonic transducer** and **hydrophone** can be moved relative to each other by an amount large enough to permit the active element of the **hydrophone** to be positioned at any point in the acoustic field at which measurements are required.

Means shall be incorporated to minimize effects on the measurement of reflection from any part within the water bath or the walls (see also 5.2.3.2).

In a direction parallel to the **beam axis** for non-automatic scanning systems or the symmetry axis of the **azimuth plane** for automatic scanning systems, the wall of the water bath should be at a distance from the **ultrasonic transducer** which is significantly greater (30 % to 100 %) than the maximum separation distance between the **ultrasonic transducer** and the **hydrophone**.

In a direction perpendicular to the **beam axis** for non-automatic scanning systems or the symmetry axis of the **azimuth plane** for automatic scanning systems, the wall of the water bath should be at a distance which is significantly greater (30 % to 100 %) than the maximum distance of the **hydrophone** from the **beam axis** in the case of non-automatic scanning systems, or from an extreme **scan line** in the case of automatic scanning systems.

NOTE 1 The size of the **hydrophone** ~~should be considered~~ also needs consideration; for membrane **hydrophones**, extra width in the direction perpendicular to the **beam axis** might be needed.

NOTE 2 The criteria for the choice of the size of the water bath referred to above are adequate for **pulse durations** less than 10 µs. For longer **pulse durations**, refer to 5.2.2.1 and [26].

5.2.3.2 Lining material

The measurements should be performed under conditions that approximate an acoustic free field. In the case of **ultrasonic transducers** excited under continuous wave conditions, acoustic absorbers should be placed to intercept as much of the ultrasound incident on the walls of the water bath as is possible. For pulsed **ultrasonic transducers**, and when techniques using gated signals are employed for detection of the **hydrophone** signal, it is not essential to use acoustic absorbers. However, it is often advisable to place absorbers on the walls of the water bath at positions so that they intercept the main incident acoustic field from the **ultrasonic transducer**.

The following tests may be used to determine the necessity for acoustic absorbers.

The criterion that may be applied is that acoustic absorbers should be used if reflected ultrasound increases the general background noise level of the **hydrophone** signal uniformly or if spurious **hydrophone** signals are detected in the vicinity of the main received signal.

A convenient test for the presence of spurious signals consists in changing the distance between the **ultrasonic transducer** and the **hydrophone** while observing the signal with an oscilloscope. Some spurious signals are observed to move at least twice the speed of the directly received signal, others are received in an incorrect time window when comparing the **ultrasonic transducer** to **hydrophone** distance. This test is possible only on pulsed systems.

With continuous wave excitation, it is necessary to observe phase changes and distortion of the main signal when the **ultrasonic transducer** is moved. A partial standing wave pattern may also be observed in many cases.

The free field conditions will be met sufficiently when the overall echo is reduced by more than 25 dB. Various methods may be used to check the ~~compliance~~ conformity of the echo reduction of the tank lining materials used, with this subclause. ~~One example that may be used to check the absorbing or scattering materials used is given in Annex B.~~ The procedures described in IEC TS 63081 can be applied to check the absorbing or scattering materials.

5.2.3.3 Water quality

For measurements in high pressure fields or on high power continuous wave excited **ultrasonic transducers**, cavitation effects can be significant, and, in this case, degassed water should be used (see Annex G for guidance).

The water should be distilled or de-ionized water at a known temperature. When a single-layer, electrically unshielded membrane [polyvinylidenefluoride (PVDF)] **hydrophone** is used, the electrical conductivity of the water should be less than 5 µS cm^{-1}.

5.3 Requirements for data acquisition and analysis systems

The transfer characteristics of the data acquisition and analysis system shall be adequate to ensure that, when used in combination with the **hydrophone**, pre-amplifier and amplifier, the requirements of 5.1.6 to 5.1.9 are met for the combination.

5.4 Recommendations for ultrasonic equipment being characterized

If the scanning in automatic scanning systems can be "frozen", appropriate acoustic measurements should be undertaken to ensure that there is no significant variation between a "frozen" beam and a scanning beam.

NOTE 1 This exercise is not trivial and depends on the type of scanning system. Also, true determination of temporal average parameters is not possible for a "frozen" beam.

If an electrical signal synchronized to the excitation of the **ultrasonic transducer** or **ultrasonic transducer element group** is not available, alternative methods may be used to obtain such a trigger signal.

NOTE 2 Such alternative methods include the use of an external electromagnetic pick-up coil or an auxiliary acoustic sensor placed in the ultrasonic field. See [27], [28], [29].

In case an **ultrasonic transducer** or **ultrasonic transducer element group** radiates ultrasound without any sequence of repetition, it will not be possible to synchronize the measurement system in the way described in this document. A subset of acoustic measurements, mostly related to safety aspects, is described in Annex F and may be useful when synchronization cannot be achieved.

Any system that controls the acoustic output of the **ultrasonic transducer** as a result of changing acoustic impedance should be switched off. In case this cannot be achieved, an additional measurement **uncertainty** should be taken into account.

6 Measurement procedure

6.1 General

The procedures described in Clause 6 and in Clause 7 are those that are particularly suitable for the characterization of ultrasonic fields using piezoelectric **hydrophones**. Other procedures based on the use of piezoelectric **hydrophones** may be employed provided equivalence with the techniques described in Clause 6 is demonstrated.

6.2 Preparation and alignment

6.2.1 Preparation

It may be necessary to seal various parts of the **ultrasonic transducer** to prevent ingress of water, especially around the cable entry point if the whole of the device is immersed. The manufacturer's advice should be sought.

Prior to use, the surfaces of the **ultrasonic transducer** and the **hydrophone** should be checked for contamination. If this is present, the surfaces should be cleaned according to the manufacturer's instructions. Any special precautions should be followed for the reliable use of **hydrophones** or **transducers** which may be specified by the manufacturer or which may have been found necessary by the user, such as immersion of a **hydrophone** for a certain time before use.

On insertion of both the **ultrasonic transducer** and the **hydrophone** in the water, care should be taken to ensure that all air bubbles are removed from the active faces. Checks should be made during the course of the measurements to ensure bubbles do not appear.

6.2.2 Aligning an ultrasonic transducer and a hydrophone

The z-axis of the **hydrophone**, which is the direction of maximum sensitivity, shall be aligned such that it is parallel to the direction of propagation of the ultrasound. A proper alignment procedure is given in IEC 61828.

6.3 Measurement

Make the measurements with an appropriate **hydrophone assembly**. Carry out observation at any point for long enough that a fully representative part of the acoustic signal is sampled. Typically, this would be less than one second.

Ensure that the **bandwidth**, sampling rate and/or temporal resolution of the acquisition system are sufficient to accurately represent the **hydrophone** signal.

NOTE 1 New technology oscilloscopes and digital capture cards are now available which allow extremely long record lengths to be captured and analysed. In general, use of such a device is likely to be the most flexible way to determine all the necessary parameters.

NOTE 2 Since it is no longer assumed that the acoustic signal will repeat, equivalent-time sampling is not possible and, consequently, the single-shot digital **bandwidth** will need to be sufficient to accurately represent the **hydrophone** signal.

6.4 Analysis

6.4.1 Corrections for restricted bandwidth and spatial resolution

Corrections shall be applied if the measurements are affected by a limited **bandwidth** (see 5.1.7) or cable resonances (see 5.1.10). ~~If the requirements for the deconvolution method are satisfied, the methods given in Annex D might produce more accurate results.~~ If the narrow-band requirements (see 5.1.7.1) are not fulfilled the deconvolution method shall be applied (see 5.1.7.2).

Corrections shall be applied if the measurements are affected by spatial averaging effects as identified in 5.1.6.2. Corrections shall be made following the methods given in Annex E.

6.4.2 Uncertainties

In evaluating and expressing the **uncertainty** in the calibration, the guidance provided by ISO/IEC Guide 98-3:2008 [see Clause 2] shall be followed.

More guidance on assessment of **uncertainties** is given in Annex I.

7 Beam characterization

7.1 General

Table 1 provides a guide to the acoustic parameters that may be used to specify the acoustic output of various types of medical ultrasonic equipment.

Table 1 – Acoustic parameters appropriate to various types of medical ultrasonic equipment

Equipment type		Primary pressure parameters	Derived intensity parameters	Other parameters
Pulse-echo	– static	1, 2	4 to 6	7, 8, 10 to 16, 18 to 20
	– auto scanning	1, 2	4 to 6	7, 8, 10 to 20
Doppler	– vascular	1[a], 2	4 to 6	7, 10, 11, 14, 18, 19
	– foetal heart	1[a], 2	4 to 6	7, 10, 11, 14, 18, 19
	– pulsed	1, 2	4 to 6	7, 8, 10 to 16, 18 to 20
Therapy (physical)	– continuous	1[a], 2, 3	5, 6	7, 9, 12, 14, 18, 19
	– tone-burst	1[a], 2, 3	4 to 6	7, 9, 12, 14 to 16, 18, 19

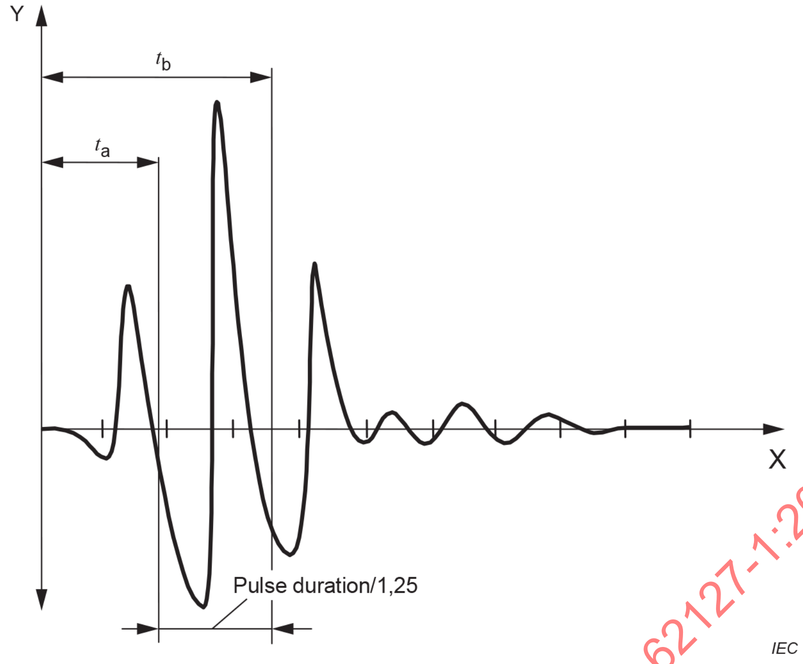
NOTE Key to table as follows:

	Clause			Clause	
1	3.50	Peak-compressional acoustic pressure	8	3.11	Beamwidth
2	3.51	Peak-rarefactional acoustic pressure	9	3.7	−20 dB beam area
3	3.60	RMS acoustic pressure	10	3.7	−6 dB beam area
4	3.70	Spatial-peak pulse-average intensity	11	3.47	−12 dB output beam dimensions
5	3.72	Spatial-peak temporal-average intensity	12	3.38	Local distortion parameter
6	3.69	Spatial-average temporal-average intensity	13	3.1	Acoustic pulse waveform
7	7.3.2.4	Derived ultrasonic power (or from IEC 61161)	14	3.16 to 3.19	Location of any of the parameter values
			15	3.54	Pulse duration
			16	3.58	Pulse repetition rate
			17	3.64	Scan repetition rate
			18	3.3	Acoustic-working frequency
			19	3.90	Ultrasonic transducer element group
			20	3.91	Ultrasonic transducer element group dimensions

[a] For this type of application the peak-compressional acoustic pressure is assumed to be of equal magnitude to the peak-rarefactional acoustic pressure.

Subclause 7.2 deals with the determination of some of the primary pressure parameters.

NOTE See Figure 4 for a schematic representation of some of the pulse parameters.



Key

t_a time to reach the 10 % value of *ppsi*

t_b time to reach the 90 % value of *ppsi*

X time

Y pressure

Figure 4 – Schematic diagram of the method of determining pulse duration

7.2 Primary pressure parameters

7.2.1 General

With the **ultrasonic transducer** and **hydrophone** mounted in accordance with 5.2.2, 5.2.3 and 6.2, any of the following acoustic parameters can be determined using the definitions listed in Clause 3.

NOTE When measurements are being made in order to ~~comply~~ conform with an individual standard (for example IEC 62359 or IEC 61157), the parameters required are those specified in that standard.

In the case of measurements made in a specified plane, the position of the plane from the face of the **ultrasonic transducer** shall be stated and the reported values shall be described as representing that plane only:

– **beamwidth** specified at −6 dB level;
– **beamwidth** specified at −12 dB level;
– **beam area** specified at −20 dB level;
– **beam area** specified at −6 dB level;
– **output beam dimension**;
– **scan-area**;
– location of the **spatial-peak temporal-peak acoustic pressure**;
– location of the maximum of the **pulse-pressure-squared integral**;
– location of the **spatial-peak temporal-average intensity**;
– **ultrasonic scan line separation**;
– **ultrasonic transducer element group dimensions**;

– **pulse repetition rate**;
– **scan repetition rate**;
– **pulse duration**;
– **arithmetic-mean acoustic-working frequency** or **magnitude-weighted acoustic-working frequency**;
– **acoustic pulse waveform**;
– **local distortion parameter**;
– **peak-compressional acoustic pressure**;
– **peak-rarefactional acoustic pressure**;
– **spatial-peak RMS acoustic pressure**.

NOTE **Arithmetic-mean acoustic-working frequency** is equivalent to center frequency in [30].

7.2.2 Peak-compressional acoustic pressure and peak-rarefactional acoustic pressure

A systematic search shall be made to locate the point or points of **peak-compressional acoustic pressure** and **peak-rarefactional acoustic pressure**.

NOTE Particular regions of interest are those areas where on the **beam axis** maxima or minima of any of these pressures occur.

Reporting of **peak compressional acoustic pressure** should be accompanied by a description of any regularization filter used (see 5.1.7.2.3, NOTE 6). At a minimum, that description should specify the −3 dB corner frequency of the regularization filter.

7.2.3 Spatial-peak RMS acoustic pressure

A systematic search shall be made to locate the point of **spatial-peak RMS acoustic pressure**.

NOTE 1 Particular regions of interest are those areas where on the **beam axis** maxima or minima of this pressure occur.

Measurements shall be made over an integral number of **acoustic repetition periods** and shall include all parts of the **acoustic repetition period** when there is ultrasound incident on the **hydrophone**.

In the case of ~~automatic~~ **scanning** ~~systems~~ **modes**, in order to determine the **RMS acoustic pressure** over the **scan repetition period**, it is essential to measure the received signal from consecutive **ultrasonic scan lines**. This received signal corresponds to excitations from consecutive **ultrasonic transducer element groups**, in the case of multi-element **ultrasonic transducers**, or from consecutive rotational **ultrasonic scan lines** in the case of sector scanners or phased-array scanners.

~~In most cases however,~~ For ultrasonic equipment exhibiting short pulse waves, it is more appropriate to determine the **pulse-pressure-squared integral** (see 7.3.2).

NOTE 2 With existing **hydrophones**, it can be essential to rotate the **hydrophone** about its axis, which is perpendicular to the **azimuth plane**, in order to maximize the received signal in each case.

7.2.4 Local distortion parameter

The propagation of ultrasound in water at the acoustic pressures and frequencies frequently encountered in medical ultrasonic fields is not a linear process and the **acoustic pulse waveform** is often distorted as a result. In diffractive fields, enhanced differences exist between the **peak-compressional acoustic pressure** and the **peak-rarefactional acoustic pressure**. To determine the significance of the distortion in the characterization of ultrasonic fields, the degree of nonlinear propagation can be ~~predicted~~ quantified by calculation of the **local distortion parameter**, σ_q (see 3.38), according to IEC TS 61949.

The following regimes ~~may~~ can be defined.

a) σ_q < 0,5: little nonlinear distortion has occurred. The amplitude at f_{awf} differs by less than 5 % from the value in the absence of nonlinear effects.

b) 0,5 ≤ σ_q ≤ 1,5: considerable distortion has occurred. A broadband **hydrophone** should be used with a sensitivity that ~~varies according to~~ meets the requirements of 5.1.7.1. The amplitude in a one half octave band centred at f_{awf} will differ from its value in the absence of nonlinear effects by between 5 % and 25 %.

c) σ_q > 1,5: considerable nonlinear distortion and also attenuation at f_{awf} has occurred. A broadband **hydrophone** should be used as in b) above. The amplitude in a one half octave band centred at f_{awf} will differ by more than 25 % from the value in the absence of nonlinear effects.

NOTE In b) and c) above, ~~the upper frequency of the **bandwidth** will often exceed 15 MHz~~ the acoustic pressure spectra $\mathcal{F}(p(t))$ are likely to contain a significant portion in the frequency range of several times the **acoustic-working frequency**, and within waveform deconvolution (see 5.1.7.2) broadband calibration data of the **hydrophone** are needed.

~~NOTE 2 The **local distortion parameter** is expected to be a reliable parameter for predicting the amount of nonlinear distortion, see [2].~~

7.3 Intensity parameters ~~using instantaneous~~ derived from acoustic pressure

7.3.1 General

As **hydrophones** measure acoustic pressure, it is appropriate that the specification of quantities based on **hydrophone** measurements ~~should~~ be given in terms of acoustic pressure. Hence the parameters given in 7.2 and in Clause 3 shall be the preferred parameters for specification.

Under conditions when it is reasonable to assume plane progressive wave propagation, it is possible to convert the measured **instantaneous acoustic pressure** parameters to true intensity. If this is done, then it shall be clearly stated that the plane progressive wave approximation has been used.

In this case the **instantaneous intensity** is approximated by the **derived instantaneous intensity**, $I(t)$, given by

$$I(t) = p(t)^2 / \rho c \tag{18}$$

where

ρ is the density of water;

c is the velocity of sound in water (see Annex B).

The following intensity parameters may be determined from the pressure parameters:

– **spatial-peak temporal-peak intensity** $I_{sptp} = (p_{sptp})^2 / \rho c$ (19)

– **spatial-peak temporal-average intensity** $I_{spta} = (p_{spr})^2 / \rho c$ (20)

– **spatial-average pulse-average intensity** I_{sapa}

– **spatial-average temporal-average intensity** I_{sata}

– **time-window-average intensity** $I_{w,\Delta t/s}(t)$.

The procedures used for the determination of the ~~last~~ first two parameters shall be similar to those for the equivalent acoustic pressure parameters. However, in this case the parameter recorded at each point in the acoustic field shall be the square of the **instantaneous acoustic pressure**.

NOTE If the **local distortion parameter** exceeds 0,5, then the conversions of measured pressure parameters to intensities might not be valid or sufficiently accurate [31].

7.3.2 Intensity parameters using pulse-pressure-squared integral

7.3.2.1 Pulse duration

The **pulse duration** is equal to 1,25 times the 10 % to 90 % rise time of the time integral of the square of the **instantaneous acoustic pressure**. The points of time, t_a and t_b, at which this time integral is 10 % and 90 % of the **pulse-pressure-squared integral**, respectively, follow from Formula (21) and Formula (22).

~~$$\frac{1}{M^2}\int_{t_1=0}^{t_a} U^2(t)\,dt = 0{,}1\,ppsi$$ and~~

~~$$\frac{1}{M^2}\int_{t_1=0}^{t_b} U^2(t)\,dt = 0{,}9\,ppsi$$~~

$$\frac{1}{M^2}\int_{t_1=0}^{t_a} u^2(t)\,\mathrm{d}t = 0{,}1\,ppsi \quad (21)$$

$$\frac{1}{M^2}\int_{t_1=0}^{t_b} u^2(t)\,\mathrm{d}t = 0{,}9\,ppsi \quad (22)$$

where

M is the general term of the **hydrophone** sensitivity;

~~U~~$u(t)$ is the measured output voltage of the **hydrophone**.

The **pulse duration** shall then be calculated as

$$t_d = 1{,}25(t_b - t_a). \quad (23)$$

7.3.2.2 Spatial-peak pulse-average intensity

Spatial-peak pulse-average intensity shall be calculated with the maximum value of the **pulse-pressure-squared integral** as measured on the **beam axis**, using:

$$I_{\text{sppa}} = \frac{1}{t_{\text{d}} \rho c} ppsi \qquad (24)$$

where

ρ is the density of water;

c is the velocity of sound in water (see Annex B);

ρc is the characteristic acoustic impedance of ~~distilled~~ pure water (= 1,48 × 10^6 kg m^{-2} s^{-1} at 20 °C);

t_{d} is the **pulse duration**.

7.3.2.3 Spatial-peak temporal-average intensity

For the **non-scanning mode** the **spatial-peak temporal-average intensity** is calculated with the maximum value of the **pulse-pressure-squared integral** value in a single beam, using:

$$~~I_{\text{spta}} = \frac{ppsi}{\rho c} prr~~ \qquad I_{\text{spta}} = \frac{prr}{\rho c} \max_z \left[ppsi(z) \right] \qquad (25)$$

where

prr is the maximum **pulse repetition rate** of the **non-~~auto~~ -scanning mode**.

For a **scanning mode** (e.g. automatic B-mode) the I_{spta} value shall be measured including the contribution of overlapping **ultrasonic scan lines**. It means that more **pulse-pressure-squared integral**(s) are processed, indicated by the sum of **pulse-pressure-squared integral**(s):

$$~~Sppsi = ... + ppsi_{c-2} + ppsi_{c-1} + ppsi_c + ppsi_{c+1} + ppsi_{c+2} ...~~$$

~~where~~

~~$ppsi_c$ is the **pulse-pressure-squared integral** belonging to the central scan line;~~

~~$ppsi_{c+1}$, $ppsi_{c-1}$, etc., are the **pulse-pressure-squared integral**(s) of diminishing values of the successive adjacent **ultrasonic scan lines**.~~

$$Sppsi = ... + n_{\text{pps,c-2}} ppsi_{c-2} + n_{\text{pps,c-1}} ppsi_{c-1} + n_{\text{pps,c}} ppsi_c + n_{\text{pps,c+1}} ppsi_{c+1} + n_{\text{pps,c+2}} ppsi_{c+2} ... \qquad (26)$$

where

$ppsi_c$	is the **pulse-pressure-squared integral** belonging to the central scan line;
$ppsi_{c+1}$, $ppsi_{c-1}$, etc.,	are the **pulse-pressure-squared integrals** of diminishing values of the successive adjacent **ultrasonic scan lines**;
$n_{\text{pps,c+1}}$, $n_{\text{pps,c-1}}$, etc.,	represent the number of repeating pulses per **ultrasonic scan line**.

From the **scan repetition rate** and the number of **ultrasonic scan lines**, the **ultrasonic scan line separation** at the depth where the maximum I_{spta} will be found is calculated. Alternatively, the **ultrasonic scan line separation** may be found by scanning the **hydrophone** in the scan direction and measuring the distances between the maxima found in the scan.

Using this **ultrasonic scan line separation**, the contribution of adjacent **ultrasonic scan lines** can be calculated from the results of a lateral line scan in the **scan plane**. In the summation of the $ppsi$ values, all contributing **ultrasonic scan lines** are to be included over a period of time sufficiently long to include all significant acoustic information.

The **spatial-peak temporal-average intensity** for the ~~non-~~**scanning mode** then results in

$$I_{\text{spta}} = \frac{Sppsi}{\rho c} srr \qquad I_{\text{spta}} = \frac{srr}{\rho c} \max_{z} \left[Sppsi(z) \right] \tag{27}$$

where

srr is the maximum **scan repetition rate** of the **scanning mode**.

7.3.2.4 Derived ultrasonic power

If the determination of total ultrasonic power P of a single, stationary, beam is done by means of planar scanning, then it shall be performed with a calibrated **hydrophone** in accordance with IEC 62127-2, based on Formula (28):

$$P = \iint_{s} I_{\text{TA}}(x,y) dx dy \qquad P = \iint_{s} I_{\text{ta}}(x,y) \mathrm{d}x \mathrm{d}y \tag{28}$$

where

~~I_{TA}~~ $I_{\text{ta}}(x,y)$ is the **temporal average intensity** at the point defined by the orthogonal coordinates x and y.

The energy E of the beam is calculated as the summation of all contributions of the $ppsi(x,y)$ at all points in a scanned area:

$$E = \frac{dS}{\rho c} \sum_{i} ppsi(x_i, y_i) \tag{29}$$

where

dS is the step area, i.e. the product of distance dx and dy between two successive measuring points (samples) in the scanned area, assuming that dx and dy are both constant throughout the scan and that the scan has a rectangular geometry.

The total ultrasonic power then follows from

$$P = E \, prr \tag{30}$$

The total ultrasonic power may also be calculated from

$$P = \frac{dS}{\rho c} \sum_i p_{\mathrm{RMS}}^2 (x_i, y_i) \qquad (31)$$

In the **scanning mode**, the total ultrasonic power for each mode of operation may be calculated from

$$P = E\,srr\,M\,n \qquad P = E\,srr\,m\,n_{\mathrm{pps}} \qquad (32)$$

where

E is the energy of the beam, as used before;

M m is the number of **ultrasonic scan lines** per image for spatial distribution;

n is the **number of** excitations of each **scan line**.

n_{pps} is the **number of pulses per ultrasonic scan line**.

The total ultrasonic power during the **scanning mode** will be the sum of all ultrasonic powers during the acting operation modes.

NOTE 1 The method is specifically useful in circumstances where a commercially available sensitive enough radiation force balance is not sensitive enough available or where the physical dimensions or **acoustic-working frequency** of the ultrasound transducer do not allow using a radiation force balance. Usually, the measurement of **total ultrasound power** is more accurate to be measured by means of the radiation force method (see IEC 61161:2006).

NOTE 2 Formula (30) applies to **scanning modes** or **non-scanning modes** only if E is the same for each pulse.

NOTE 3 Formula (32) assumes the same **number of pulses per ultrasonic scan line** n_{pps} for the specific **scanning mode**.

NOTE 4 Formula (32) assumes that the acoustic power of each pulse in each of the m **ultrasonic scan lines** is the same. This is not true if different scan lines use different pulse types or aperture sizes.

8 Requirements for specific ultrasonic fields

8.1 General

The requirements listed in Clause 8 are either an addition to or supersede the applicable ones specified in Clause 5. See also Annex H. For the determination of absolute values of acoustic pressure or derived intensity (see 3.14), the **hydrophone** shall be calibrated in accordance with IEC 62127-2.

8.2 Diagnostic fields

8.2.1 Simplified procedures and guidelines

The measurement of the **pulse-pressure-squared integral** is required for many aspects of ultrasonic field characterization.

In cases where the **acoustic pulse waveform** does not change shape within any particular measurement plane perpendicular to the **beam axis**, the **peak acoustic pressure** may be used instead of the **pulse-pressure-squared integral**.

NOTE 1 Frequently, this situation is encountered in continuous wave ultrasonic fields such as continuous wave Doppler and physiotherapy transducers.

If all the acoustic scan lines are assumed to be of equal magnitude and beam shape, the overlapping scan line contribution may be determined knowing the beam shape and the separation between scan lines in the measurement plane.

All acoustic scan lines should be sampled in order to locate the one with the largest **peak acoustic pressure**.

NOTE 2 In practice, the variation between the acoustic output of different scan lines will depend on the type of scanner. For sector scanners using rotating single-element transducers with a constant acoustic coupling path, the difference would be expected to be small. In this case, sampling the **central scan line** and the two extreme scan lines at the edge of the sector would be undertaken and an assessment made on whether it is necessary to determine the output of other scan lines. If the difference between the **peak acoustic pressures** is less than 10 %, ~~there should be no need to measure other lines~~ it is unlikely that other scan lines need to be measured other lines.

8.2.2 Pulsed wave diagnostic equipment

8.2.2.1 Diagnostic fields in general

A **hydrophone** with an active element of diameter of approximately 0,5 mm or less shall be used. However, in addition the recommendations of 5.1.6.1 and 5.1.6.2 should be followed.

The repeatability of the positioning systems shall be ±0,01 mm for three orthogonal adjustments for the **hydrophone** (or transducer if the latter is the item that is scanned).

For waveforms that are distorted by nonlinear propagation effects, i.e. those with a **local distortion parameter** σ_q (see 3.38) greater than 0,5, either a **hydrophone** with adequate **bandwidth** (see 5.1.7) shall be chosen~~; corrections shall be applied (see Annex D); or an additional uncertainty in the measurement shall be taken into account~~, or voltage-to-pressure conversion shall be performed using deconvolution of the frequency response of the **hydrophone** (see 5.1.7.2 and Annex D).

~~PVDF hydrophones of the membrane or needle type are essential (see Clause B.9) as opposed to ceramic needle types.~~

Ceramic needle type **hydrophones** are not recommended (see Clause B.9).

NOTE 1 In practice, the accuracy and repeatability of positioning systems is most important in the direction perpendicular to the propagation direction and, in most cases, ±0,05 mm is often adequate. In the propagation direction, an accuracy of ±0,1 mm is often adequate for most measurement situations. The highest accuracy would be required for highly focused fields (wide aperture) and at high frequencies (see 5.2.2.3).

NOTE 2 In case of distorted waveforms, additional demands are placed on the angular alignment because of the dependence of the directional response on frequency. Under these conditions, it is important to optimize the rotation of the **hydrophone** to ensure the maximum received signal (see 5.2.2).

NOTE 3 At typical focal distances, the square law relationship between acoustic pressure and intensity is usually assumed in order to derive intensity parameters. This assumption is made despite the **uncertainty** associated with the nonlinear distortion that can take place.

8.2.2.2 Diagnostic fields in the absence of scan-frame synchronization

The ultrasound fields generated by clinical imaging scanners have become increasingly complex as technology has advanced. The parameters defined in Clause 3 to describe the spatial and temporal variation of pressure and intensity in the ultrasound field work well for unscanned fields such as those used for pulsed Doppler or M-mode. However, it is becoming increasingly difficult to use all of these definitions for the complicated pulse sequences generated in scanned modes such as colour-flow imaging. In some cases, it might not be possible to determine an **acoustic repetition period** for these sequences.

A modified set of acoustic parameters that might be more appropriate to modern imaging equipment is outlined in Annex F.

8.2.3 Continuous wave diagnostic equipment

A **hydrophone** with an active element of diameter approximately 0,5 mm or less shall be used. However, in addition the recommendations of 5.1.6.1 and 5.1.6.2 should be followed.

The repeatability of the positioning systems shall be ±0,01 mm for three orthogonal adjustments for the **hydrophone** (or transducer if the latter is the item that is scanned).

For waveforms that are not distorted by nonlinear propagation effects, i.e. those where the **local distortion parameter** σ_q (see 3.38) is smaller than 0,5, it is not necessary to use a broadband **hydrophone** (see 5.1.7).

In ultrasonic fields where the **peak acoustic pressure** occurs close to the face, e.g. at distances less than the minimum **output beam dimension**, the approximation for ultrasonic intensity (see 7.3) may be made, provided that an appropriate **uncertainty** is taken into account.

PVDF or ceramic needle devices (see Clause B.9) are satisfactory for measurements on continuous wave Doppler transducers. Membrane **hydrophones** may be used providing care is taken to ensure the reflection from the membrane does not interfere with the output from the **ultrasonic transducer** (see 5.2.2.2).

8.2.4 Diagnostic equipment with low acoustic output

For **hydrophone** measurements on diagnostic systems that fulfil the criteria of IEC 60601-2-37:2007, 201.12.4.2 a) and b) to be exempt from the requirement to display thermal and mechanical indices, the narrowband approximation can be applied even if the criteria of 5.1.7.1 cannot be fulfilled. When using this simplification, the additional measurement **uncertainty** reflecting the limitations of a narrowband measurement of a broadband signal shall be considered, in particular, when comparing output data against thresholds.

8.3 Therapy fields

8.3.1 Physiotherapy equipment

Methods and requirements listed in IEC 61689 or IEC 63009 shall be followed depending on the **acoustic-working frequency** of the equipment.

For waveforms that are not distorted by nonlinear propagation effects, i.e. those where the **local distortion parameter** σ_q (see 3.38) is smaller than 0,5, it is not necessary to use a broadband **hydrophone**.

If an absolute value of acoustic pressure or derived intensity (see 3.14) is needed, the **hydrophone** shall be calibrated in accordance with IEC 62127-2 at the f_{awf}. For **acoustic-working frequencies** f_{awf} below 0,5 MHz, calibration shall be in accordance with IEC 60565-1.

For fields generated by ultrasound physiotherapy devices a linear response, as referred to in 5.1.8, up to 1 MPa is generally adequate.

Measurements of effective radiating area (see for definition: IEC 61689) shall use a needle **hydrophone**, with the active element made from either polyvinylidene fluoride (PVDF) or piezoceramic. Care ~~shall~~ should be taken to ensure reflections from the needle and its support do not interfere with the measurements.

Cavitation effects can cause damage to **hydrophones** at the pressures that can be produced by physiotherapy transducers. It is, therefore, essential to use degassed water for measurements with **peak acoustic pressure** above 0,3 MPa.

The maximum **effective hydrophone** ~~radius~~ **size** used for the measurements shall be a_{max} so that:

$$a_{max} \leq \lambda/2{,}5 \tag{33}$$

NOTE 1 In most cases, in physiotherapy, the above criterion represents an **effective hydrophone** ~~radius~~ **size** larger than that recommended in 5.1.6. It has been derived from an analysis of its effect on the effective radiating area, rather than on peak pressures, and the former is less sensitive to the effects of spatial averaging.

NOTE 2 **Hydrophones** are also used to measure the beam non-uniformity ratio and the above criterion is also acceptable for those measurements [32], [33].

NOTE 3 For some **treatment heads**, ultrasound reflected back to the **treatment head** ~~may~~ can affect output power, particularly in the case of coherent reflections from absorbers with planar smooth surfaces. In these instances, an improved approximation to free field conditions ~~may~~ can be obtained by using acoustic absorbers with textured surfaces.

~~8.3.2 Hyperthermia~~

~~Specific requirements for High Intensity Focussed Ultrasound (HIFU) equipment are under development.~~

8.3.2 High intensity therapeutic ultrasonic fields

To support acoustic output characterization in accordance with IEC 60601-2-62, specific requirements on the measurement of fields generated by high intensity focused ultrasound (HIFU) and high intensity therapeutic ultrasound (HITU) are specified in IEC TS 62556 with respect to measurement at relatively low output levels and methodology for extrapolating these to higher therapeutic level fields.

For measurements at focus at clinical driving levels, the upper frequency range limit of 8 f_{awf} in the narrow-band approximation requirement according to Formulas (14) and (15) (see 5.1.7.1) shall be replaced by min [20 f_{awf}, 100 MHz], and the −3 dB cut-off frequency of the low-pass filtering within deconvolution regularization (see 5.1.7.2.3) shall be at minimum the lesser of 20 times the **acoustic-working frequency** f_{awf} or 100 MHz. Extrapolation ranges for **hydrophone** calibration data $\underline{M}_L(f)$ shall be limited to below half of the **acoustic-working frequency** towards zero and above the lesser of 20 times the **acoustic-working frequency** or 100 MHz towards the Nyquist frequency, e.g. for $0 \leq f < f_{awf}/2$ and for min [20 f_{awf}, 100 MHz] $< f \leq f_{Nyquist}$.

NOTE 1 More restrictive **bandwidth** criteria than in general are needed here for adequate waveform reproduction due to the large number of harmonics.

NOTE 2 **Hydrophone** calibration data are expected to be available up to 100 MHz and **acoustic-working frequencies** are usually below 5 MHz for high intensity ultrasonic fields.

A linear amplitude response as specified in 5.1.8 to extend up to 5 MPa may not be sufficient in many measurement situations for HIFU or HITU. If pressure signals exceed the linear amplitude range of the **hydrophone** as defined in IEC 62127-3, corrections shall be employed to compensate for the amplitude distortion within the 10 % criterion of IEC 62127-3 caused by the nonlinearity in the pressure response of the **hydrophone.** The correction shall be taken into account in determining acoustic quantities and associated **uncertainties.** If no such corrections can be implemented, or if the pressure range exceeds the damage threshold of the **hydrophone**, the **hydrophone** shall not be used.

NOTE 3 Extended linearity is needed here due to the large **peak compressional acoustic pressures** in high intensity ultrasonic fields.

NOTE 4 The maximum pressure at the surface of a **hydrophone** can be significantly higher than the measured free-field pressure due to the acoustic reflection of the incident wave. This needs to be taken into account within guidelines for **hydrophone** usage and for corrections for non-linear effects.

8.3.3 Non-focused and weakly focused pressure pulses

Specific comments on the measurement of fields generated by non-focusing pressure pulse sources for pain treatment and other applications are specified in IEC 63045.

NOTE Such pressure pulse fields are usually described using pressure parameters rather than derived intensity parameters.

8.4 Surgical fields

8.4.1 Lithotripters and pressure pulse sources for other therapeutic purposes

Specific requirements for the measurement of fields generated by pressure pulse lithotripters are specified in IEC 61846.

For fields generated by lithotripters, the linear response, as referred to in 5.1.8, should be known at least up to ~~between and including~~ 80 MPa and in cases where measurements indicate higher **peak compressional pressure** values up to 150 MPa. Any nonlinearity in the pressure response of the **hydrophone** shall be taken into account in determining acoustic quantities and associated **uncertainties**.

NOTE 1 Pressure pulses are not only used for lithotripsy, but also for the treatment of pain, for example shoulder calcification pain, tennis elbow, heel spur pain, etc. as well as for other medical applications (cardiac shockwave application).

NOTE 2 Such pressure pulse fields are usually described using pressure parameters rather than derived intensity parameters.

8.4.2 Low frequency surgical applications

For the characterization of low frequency surgical systems using a **hydrophone**, the **hydrophone** shall be calibrated in accordance with IEC 60565-1~~:2006~~.

Requirements as listed in Clause 5, Clause 6 and Clause 7 do not apply to this type of equipment.

Specific requirements for the measurement of fields generated by low frequency surgical systems are specified in IEC 61847.

8.5 Fields from other medical applications

Presently there are no specific requirements for this type of equipment.

9 ~~Compliance~~ Conformity statement

9.1 General

The acoustical parameters shall be chosen from those defined in this document. To ensure traceability, the settings should be recorded of any controls on the equipment console which might affect the field generated.

For ~~compliance~~ conformity with this document, the following shall be stated for any parameter that is reported:

a) the arithmetic mean determined from measurements on a group of n nominally identical systems, each with the acoustic output settings yielding the maximum output, where $n \geq 3$; and

b) the overall **uncertainty** of the value determined under a).

This overall **uncertainty** shall be calculated using an appropriate measure (with 95 % confidence, for 95 % of the population) of the statistical variation and the measurement **uncertainty** (at a level of confidence of 95 %).

The tolerance interval is to be understood in accordance with ISO 16269-6~~:2005~~. More guidance on assessment of **uncertainties** is given in Annex I.

Measurement **uncertainty** involves many components (see Annex I). It shall be an assessment of the contributions of all **uncertainties** (these referring to measurements made on one system). The measurement **uncertainty** shall be calculated as expanded **uncertainty** corresponding to a level of confidence of 95 %. The method of combining the **uncertainty** contributions specified by ISO/IEC Guide 98-3:2008 shall be followed.

NOTE "tolerance interval" refers to the production scatter and "**uncertainty**" refers to the measurement method.

9.2 Maximum probable values

A requirement of the type "shall conform to" means that the measurement **uncertainty** and tolerance interval shall be included when comparing against a limit. The maximum probable values shall be determined in accordance with the following procedure:

a) measurements shall be carried out on a group of n nominally identical systems, each with the acoustic output settings yielding the maximum output, where $n \geq 3$;

b) the maximum probable value shall be calculated by linear summation of the upper tolerance limit of the one-sided tolerance interval (with 95 % confidence, for 95 % of the population) and the measurement **uncertainty** (at a level of confidence of 95 %).

The tolerance interval is to be understood in accordance with ISO 16269-6~~:2005~~. More guidance on assessment of **uncertainties** is given in Annex I.

NOTE 1 "tolerance interval" refers to the production scatter and "**uncertainty**" to the measurement method.

It may not be possible to comply with all the requirements of this document. If measurements are made for the purposes of acoustic output specification and labelling which do not comply with ~~any~~ a particular requirement then the lack of ~~compliance~~ conformity shall be clearly stated when reporting results. A statement of non-~~compliance~~ conformity shall include the relevant clause or subclause and shall give the reason for non-~~compliance~~ conformity.

NOTE 2 Selected examples of ~~non-compliance may be~~ non-conformity are as follows, where IEC 62127-1 refers to this document.

a) IEC 62127-1 was complied with, except for 5.1.7; the sensitivity of the **hydrophone** at 20 MHz was 60 % below the sensitivity at 5 MHz.

b) IEC 62127-1 was complied with, except for 5.1.9; the change in amplifier gain from 5 MHz to 20 MHz was −5 dB.

c) IEC 62127-1 was complied with, except for 5.1.6; the **effective hydrophone ~~radius~~ size** was 0,5 mm.

9.3 Sampling

For good manufacturing practice, measurements should be taken on a certain percentage of production but, exceptionally, could be taken on each manufactured unit.

For the purpose of determining the product variation of the reported parameters when full repeat measurements of all parameters are impractical, this variation may be estimated from partial repeat measurements (by repeating the measurement of a subset of the parameters).

Standard statistics on probability and confidence as given in ISO 16269-6~~:2005~~ shall apply.

Annex A
(informative)

General rationale

This Annex A provides a concise rationale for the important requirements of this document and is intended to provide background information for those who are familiar with the subject of this document but who have not participated in its development. An understanding of the reasons for the main requirements is considered to be essential for the proper application of this document. Furthermore, as medical ultrasonic equipment continues to develop, it is believed that a rationale for the present requirements will facilitate the application of this document to new equipment and facilitate any future revision of to this document.

The numbering in this Annex A refers directly to this document.

Clause 3: Many of the acoustic parameters are defined such that either a single value may be given or, alternatively, a value may be given that corresponds to measurements in a specified plane. This option permits greater flexibility in the application of this document. For instance, in the case of transducers used for physiotherapy, or divergent beam transducers such as used for foetal monitoring, it may not be appropriate to determine acoustic parameters in the plane containing the maximum **spatial-peak temporal-peak acoustic pressure**. The form of definitions used in this document permits a choice of measurement plane based on criteria other than those given in this document.

Terms 3.25 and 3.27: Both the sensitivity of a **hydrophone** when connected to an electrical load, such as an oscilloscope, and the sensitivity into an infinite impedance load (open circuit) are defined as they are both relevant to the practical application of **hydrophones**.

Term 3.38: At the high acoustic pressures generated by medical ultrasonic diagnostic equipment (**peak-compressional acoustic pressures** in the range of 0,1 MPa to 10 MPa), there can be severe distortion of the **acoustic pulse waveform**, especially in the focal region. An important aspect of this document is that it addresses these nonlinear effects that are associated with the propagation of ultrasound in water. This distortion is caused by the fact that, during an acoustic cycle, the compressional part of the wave travels faster than the rarefaction part giving rise to a progressive distortion of the waveform. In general, the degree of distortion present at any point in an acoustic field increases with the increase in a number of factors. These are the distance from the transducer, the **acoustic frequency**, the **peak acoustic pressure** at the face of the **ultrasonic transducer**, the nonlinearity parameter for the propagating medium (water) and the degree of focusing. While it is accepted that absorption and scattering of ultrasound in various types of tissue will lead to a reduction in the **peak acoustic pressure** in many medical imaging situations, for certain applications this reduction will not be significant. For instance, imaging through the eye, bladder and amniotic fluid are specific examples where much of the path is through liquid. To cope with this nonlinearity, this document includes, in the list of parameters that may be used for specification purposes (see 7.2.1), the parameter related to nonlinearity. It is the **local distortion parameter** that is an index predicting the importance of nonlinear distortion at the focus, see IEC TS 61949. From this parameter, the bandwidth of the **hydrophone/amplifier** and the need for corrections to measured peak pressures may be determined.

Terms 3.50 and 3.51: Again, both the **peak acoustic pressures** are defined as often there is a difference of up to a factor of three between them. As the **peak-rarefactional acoustic pressure** is most likely to be relevant to acoustic cavitation (the decompression part of the cycle), it is important to distinguish between them.

Term 3.87: The definition is intended to distinguish between the **ultrasonic scan lines** that intersect the chosen plane at gradually changing positions during the acoustic scan, and those that essentially do not. For instance, those in the latter category would be multiple excitations of the same **ultrasonic transducer** or **ultrasonic transducer element group** for focusing at different depths or for interlaced Doppler lines in duplex scanners.

Subclause 5.1.7: Broad **hydrophone bandwidths** are important for characterizing the temporal characteristics of medical ultrasound fields when short pulses are used or when significant nonlinear distortion is present. One consequence of nonlinear distortion is that an increased high-frequency response is necessary due to the higher harmonics generated [9]. In [9] it was found that a ±3 dB **bandwidth** of at least eight times the **acoustic-working frequency**, f_{awf}, was reasonable for keeping measurement errors below about 5 %. A lower limit of the frequency band used in the determination of the **hydrophone bandwidth** well below f_{awf} is desirable also, particularly for accurate measurement of the **peak-rarefactional acoustic pressure**, p_r [10]. One reason for increased low-frequency **hydrophone** response is that the shorter the pulse, the broader is the spectrum below as well as above the centre frequency. Additionally, for p_r, the waveform asymmetry resulting from the combined effects of source diffraction and nonlinear propagation causes the portion of the pulsed waveform where p_r occurs to be dominated by low-frequency components. In [10], which contains both simulations and measurements of the effects of band-limited response on short pulses, based on the **hydrophone assembly** having a single-pole, high-pass response, it was found that to reduce measurement errors to less than 5 % to 10 %, the **hydrophone assembly** lower limit of the frequency band used in the determination of the **hydrophone bandwidth** should extend to at least an order of magnitude below f_{awf}. Thus, in this document it is recommended that, if possible, the lower and upper limits for the combined frequency response of all components used to condition, amplify, or record the pulsed waveforms be set at f_{awf}/16 and 8 f_{awf}. For practical reasons, the lower and upper limits of the frequency band used in the determination of the **hydrophone bandwidth** are f_{awf}/2 and ~~the lesser of 8 f_{awf} or 40 MHz~~ 8 f_{awf}. For the frequency ranges below f_{awf}/2 and above the lesser of 4 f_{awf} and 100 MHz, however, the **hydrophone** calibration data may be extrapolated if they are not available from calibration measurements (see Annex D). If narrow-band requirements are not fulfilled, broadband measurements using waveform deconvolution are performed in accordance with 5.1.7.2 and similar **bandwidth** criteria have been adopted for this method.

NOTE 1 An absolute upper limit of 40 MHz was specified in IEC 62127-1:2007 due to the limitation of the accompanying **hydrophone** calibration standard IEC 62127-2:2007. However, since then calibration methods have been extended [11], [18], [34], [35], [36], [37], [38] and this limitation has been dispensed with.

NOTE 2 The upper extrapolation frequency limit of 4 f_{awf} or 100 MHz rather than 8 f_{awf} is allowed to achieve practicability in particular for f_{awf} > 12 MHz and for f_{awf} > 25 MHz, respectively.

NOTE 3 More restrictive **bandwidth** criteria are required in 8.3.2 for high intensity therapeutic ultrasonic fields.

Clause 7: A large number of acoustical parameters are defined in Clause 3 and given here. These provide the basis for the specification of a wide range of ultrasonic fields, although emphasis has been given to medical ultrasonic equipment. However, for any particular equipment, it is expected that only a small group of these acoustical parameters will be chosen, for instance, for the purpose of acoustic output labelling.

Clause 9: It is not the purpose of this document to specify the acoustical parameters for acoustic output labelling. Clause 9, however, provides the necessary guidelines for the declaration of acoustical parameters for the purpose of acoustic output labelling. Provision is made for the reporting of results when the measurement procedures do not meet all the requirements of this document.

A general discussion on the accuracy of the measurement of acoustic quantities is given in Annex I.

Annex B
(informative)

Hydrophones and positioning

B.1 General

There are four basic types of **hydrophone** currently in use. Two **hydrophone** constructions employ an active element made from either a piezoelectric ceramic or polymer (usually polyvinylidene fluoride, PVDF), which is supported at the end of a needle-like structure. The third type is the membrane **hydrophone**, which uses a large sheet of PVDF, the central region of which is piezoelectrically activated. The fourth type is the fibre-optic **hydrophone**. Refer to Clause B.9 for a more detailed assessment of the four types of **hydrophone**.

None of these current designs of **hydrophone** yields devices that meet all the requirements of this document over the full frequency range ~~50 kHz to 40 MHz~~ of ultrasonic applications. Preliminary reports concerned with the performance of optic and fibre-optic **hydrophones** indicate that in the future they could meet these requirements and eliminate the need for spatial averaging corrections (see [39], [36], [40]). Nevertheless, the relative importance of the requirements depends on the particular ultrasonic field to be characterized. For instance, in the **far field** of a plane piston **ultrasonic transducer**, the size of the active element can be up to two or three times the acoustic wavelength. Also, for acoustic pressures less than 0,1 MPa, the **bandwidth** of the **hydrophone** is less critical because nonlinear distortion is unlikely to be significant at the propagation distances normally encountered. Likewise, for measurements on pulsed fields, reflections from membrane **hydrophones** are less important than for continuous wave fields.

B.2 Electrical loading considerations

The **end-of-cable loaded sensitivity** of a **hydrophone**, (see 5.1.3), should be determined from its **end-of-cable open-circuit sensitivity** using the method described in IEC 62127-2. Also, in IEC 62127-2 the effects of changing the loading conditions are described.

B.3 Hydrophone signal amplifier

The purpose of a **hydrophone** signal amplifier is to provide a buffer between the **hydrophone** and the measurement system. Such a buffer overcomes cable resonance effects at high frequencies and provides extra gain and a constant electrical load for the **hydrophone**. An amplifier may be incorporated in the **hydrophone** as an integral amplifier, in which case it is not possible to separate the two devices. Alternatively, it may be a separate device into which the **hydrophone** is plugged either directly or using the connector at the end of the **hydrophone** cable. Disadvantages of any **hydrophone** amplifiers are that they tend to limit dynamic range and will need a power supply, thereby adding complexity. An additional disadvantage of an integral amplifier ~~is~~ can be the need for extra power supply wires at the **hydrophone**. See also [23].

B.4 Hydrophone cable length and amplifiers

When a **hydrophone** is connected to a voltage measuring device such as an oscilloscope, or to an amplifier, it is important to consider the electrical characteristics of the resulting measurement systems.

It is not usually possible for the electrical output impedance of a **hydrophone**, excluding any integral cable, to be matched to the impedance of the cable. This is because the output impedance of a **hydrophone** usually exceeds that of the cable. Consequently, it is not practical to use an electrical load at the end of the cable that matches the cable impedance if a significant loss of signal amplitude and waveform quality is to be avoided. Hence, without an electrically matched cable and load, reflections of the signal will occur at the end of the cable, causing "ringing". These cable resonances will be maximum when the cable length equals one quarter of the wavelength of the electrical propagation in the cable. Typically, for normal coaxial cables, the resonance occurs at cable lengths (in metres) given by 50/$\{f\}$ where $\{f\}$ ~~is~~ denotes the numerical value of the frequency in MHz. Thus, at 50 MHz, a cable length of 1 m will cause resonances. The significance of resonances will depend on the mismatch of the electrical impedances at the cable/load and cable/**hydrophone** interfaces. In addition, it would be dependent on the frequency content of the **hydrophone** signal, which depends on the **bandwidth** of the **hydrophone** (excluding any integral cable). Providing the thickness resonance mode of the **hydrophone** occurs at a frequency below that of the cable resonance, the effects of cable resonance will probably be negligible.

Hence, if cable resonances occur at frequencies within the range of lower and upper limit of the frequency band used in the determination of the **bandwidth** of the **hydrophone**, the cable length should be minimized, and an amplifier placed close to the **hydrophone**. To overcome cable resonances at the output of the amplifier, such an amplifier should have an output impedance matched to any connecting cable, the cable being terminated by a load equal to the characteristic impedance of the cable. Choice of the gain and **bandwidth** of the amplifier is important in order to avoid exceeding its dynamic range. For a **hydrophone** with a sensitivity of 0,03 μV/Pa (typical 0,5 mm PVDF device) applied to measurements of diagnostic ultrasonic equipment where **peak acoustic pressures** can be as high as 10 MPa, an amplifier of unity gain with a dynamic range of 0,6 V peak-to-peak will be needed. See also [23].

Another important aspect in choosing an amplifier is to match the frequency response of the amplifier to that of the **hydrophone**. In particular, to avoid resonance problems, the −3 dB **bandwidth** of the amplifier should not exceed the frequency corresponding to the thickness resonance mode of the **hydrophone**. It is also important to ensure that, beyond the frequency corresponding to the thickness resonance mode of the **hydrophone**, the frequency response of the amplifier decreases at a rate of typically −6 dB per octave.

B.5 Transducer positioning

The following degrees of freedom should be provided for the **ultrasonic transducer**:

Rotational adjustment about three orthogonal axes, one of which should be approximately parallel to the **beam axis**.

Although continuously variable translational degrees of freedom are not essential, it may be necessary to provide some movement in order to position the **ultrasonic transducer** at different places in the tank.

The **ultrasonic transducer** is set up in the coordinate positioning system such that the axis of symmetry of its active element is parallel to the z axis of the **hydrophone** positioning system. Here, the axis of symmetry for **ultrasonic transducers** with cylindrical active elements ~~shall~~ should be the axis of the cylinder. For **ultrasonic transducers** with spherical active elements, the axis of symmetry ~~shall~~ should be the axis that passes through the geometrical centre of the sphere and approximately bisects the usable external surface of the **ultrasonic transducer**.

The **ultrasonic transducer** should be mounted in such a way that rotation about the axis of symmetry through 360° is provided.

NOTE For spherical **ultrasonic transducers** consisting of a segment of a sphere, the axis of symmetry would be the axis passing through the geometrical centre of the sphere and through the centre of the circle defining the segment. For some spherical **ultrasonic transducers** consisting of a full (or nearly full) sphere supported by a thin structure such as a tube or rod, the axis of symmetry would be the axis passing through the centre of the sphere and also through the centre of the supported area.

B.6 Alignment of hydrophones

This Clause B.6 provides useful procedures for the alignment of **hydrophones** at the point of **spatial-peak temporal-peak acoustic pressure** in a plane perpendicular to the **beam-alignment axis**.

In the case of membrane **hydrophones**, it is possible to test for correct alignment by rotating the **hydrophone** through 180° about an axis passing through the plane of the active element and noting the change in the received signal when monitoring a pulsed acoustic field. A change in the time delay between excitation and reception indicates a misalignment in the direction normal to the active element, and a change in the amplitude indicates a misalignment in the plane of the active element. In the case of continuous wave excited **ultrasonic transducers**, the same procedure can be used with respect to amplitude, and, if the **hydrophone** has already been aligned to within one quarter of an acoustic wavelength in water, fine adjustments can be made by noting the phase change on rotation.

In the case of needle **hydrophones**, it is possible to test for correct alignment by rotating the **hydrophone** through an angle less than 180° about an axis passing through the plane of the active element.

For both types of **hydrophones**, optical techniques using either a travelling microscope or a small diameter laser beam can be used. Again, the procedure would be to observe the position of the active element and its change when the **hydrophone** is rotated using the micropositioning system.

NOTE To avoid effects on the measurements made on continuous wave fields due to reflection of ultrasound from the surface of membrane **hydrophones**, the **hydrophone** ~~may~~ can be tilted. Tilting ensures that the reflected ultrasound either does not interfere significantly with the transducer or is not subsequently reflected from the transducer face, producing interference effects. Two methods ~~may~~ can be used to determine the rotation required and a correction applied to measurements for the reduction of the signal due to the directional response of the **hydrophone**.

The first method is to observe the signal from the **hydrophone** and to determine when the interference effects decrease to a negligible level when the **hydrophone** is rotated. To observe the interference effects, the **hydrophone**/transducer separation is altered by about ±0,5 mm, which will cause oscillations of the measured signal if such effects are present. The amplitude of oscillation will decrease as the angle of rotation of the **hydrophone** is increased. Usually, the angle found using this method is less than that determined using the second method, which is to determine the angle at which most of the ultrasound reflected from the membrane will miss the transducer. This angle is determined from tan ($a/2l$) where a is the geometrical radius of the transducer active element and l is the distance between the transducer face and the **hydrophone**. As an example, consider measurements made using a 0,5 mm bilaminar construction membrane **hydrophone** (thickness 0,05 mm) on a 1,5 MHz physiotherapy transducer with an active element of a diameter of 20 mm. An angular rotation of 14° is needed for measurements made at a distance of 20 mm. Correction to measurements for loss in signal due to the directional response is determined from the measurements of the directional response (see 5.1.4). For the case considered here, a correction of +6 % for acoustic pressure parameters and +12 % for derived intensity parameters is therefore needed.

B.7 Water bath lining material

~~Compliance~~ Conformity with 5.2.3.2 for overall echo reduction of an acoustic absorber ~~may~~ can be checked using the ~~following~~ procedures described in IEC TS 63081. Echo reduction should be measured at the **acoustic-working frequency** using tone-burst **ultrasound**~~, with the acoustic absorber located in the **far field** of the separately driven **ultrasonic transducer**~~. ~~The resulting **hydrophone** signal (peak-to-peak or rms), produced by the reflection from the front surface of the acoustic absorber, $U_{absorber}$, is compared to that from a perfect planar reflector, $U_{reflector}$. The acoustic absorber and the perfect reflector should be aligned near normal to the **beam axis** but angled so that the reflected signal can be intercepted by the hydrophone. The echo reduction is calculated using:~~

$$echo\ reduction = -20 \log_{10}\left[\frac{U_{absorber}}{U_{reflector}}\right] \quad (B.1)$$

A stainless steel reflector of minimum thickness 25 mm may be used to provide a good approximation of a perfect planar reflector.

B.8 Recommendations for ultrasonic equipment being characterized

To trigger the measurement system, an electrical signal should be provided synchronized to the excitation of the **ultrasonic transducer** or each **ultrasonic transducer element group**.

For automatic scanning systems, an additional trigger signal should be provided synchronized to each **acoustic repetition period**. These trigger signals should be used to permit the observation of the received signal at the **hydrophone** from any chosen **ultrasonic scan line**.

Alternatively, if the scanning in automatic scanning systems can be "frozen", a trigger signal for the chosen **ultrasonic scan line** should be provided. However, in this case, tests shall be undertaken to ensure that there is no significant variation between a "frozen" beam and a scanning beam. This exercise is not trivial and depends on the type of scanning system. Also, true determination of temporal average parameters is not possible for a "frozen" beam.

NOTE For the separation of interlaced Doppler and scan lines in certain types of duplex automatic scanning systems, it is useful to display the trigger signals on a separate oscilloscope that has a delayed time base and delayed time base output facility. This output may can be used to trigger the measurement system.

B.9 Types of hydrophones

B.9.1 Ceramic needle hydrophones

Ceramic needle **hydrophones** usually consist of a small circular disc of piezoelectric ceramic mounted on the end of a needle or pencil-like support. The active element of the **hydrophone** is backed by an acoustically absorbing material and has a size close to the diameter of the support, often in the range of 0,5 mm to 1,5 mm diameter. The signal cable inevitably passes through the ultrasonic field, which can cause problems from the triboelectric effect.

The **end-of-cable open-circuit sensitivity** of these devices is typically 0,7 µV/Pa for a ceramic needle **hydrophone** with an active element of 1 mm diameter. When carefully designed, they may have a relatively flat frequency response to about 6 MHz. However, in general, radial resonance modes and reverberations in the backing material often lead to variations of ±10 dB in the frequency response between 0,5 MHz and 15 MHz. In addition, the directional response of most ceramic needle **hydrophones** available is often unpredictable and can show significant differences from theoretical predictions. See [41] and [42]. In some cases, however, directional responses of ceramic needle hydrophones were found to be consistent with theoretical predictions [43].

B.9.2 PVDF needle hydrophones

PVDF needle **hydrophones** are similar in external physical construction to the ceramic needle **hydrophones** described in B.9.1. However, the active element is the polymer PVDF. Typically, the **end-of-cable** (1 m) **open-circuit sensitivity** of a PVDF needle **hydrophone** with a 1 mm diameter active element is 0,12 µV/Pa and the resonance frequency is beyond 25 MHz. Carefully designed PVDF needle **hydrophones** show a smooth frequency characteristic (±1,5 dB) and a predictable directional response. The effective diameter of such **hydrophones** [44] is often very close to the physical diameter of the active elements. See [23], [42], [43], [44], [45].

B.9.3 PVDF membrane hydrophones

PVDF membrane **hydrophones** consist of a thin film of PVDF stretched across an annular frame. Electrodes are evaporated onto the two surfaces and an overlap region defines the active element after it has been poled. Various designs have been produced offering different degrees of electrical shielding for the active element. Essentially, the membrane transmits most of the ultrasound when the diameter of the membrane is sufficiently large to enable the whole of the ultrasound beam to pass through it. With this design of **hydrophone**, radial resonance modes in the megahertz frequency range are eliminated, and hence they exhibit a smooth frequency response. Typically, for a 1 mm diameter active element, the **end-of-cable** (0,7 m) **open-circuit sensitivity** of membrane **hydrophones** is about 0,10 µV/Pa and the resonance frequency is at approximately 40 MHz for a 0,025 mm thick film of PVDF. The directional response at all frequencies is predictable, including the low megahertz range where membrane waves in the film give rise to larger side-lobes in the directional response. The effective diameter of such **hydrophones** differs from the physical diameter of the active elements and depends on the frequency of the received signal. See [24], [17], [42], [34], [46], [47].

B.9.4 Fibre-optic and optic hydrophones

In the fibre-optic **hydrophones** that have been developed for measurements in medical ultrasound fields, the fibre is aligned so that the end face is normal to the direction of acoustic propagation, just as the element in a piezoelectric needle **hydrophone** would be. In this configuration the fibre behaves as an extrinsic rather than intrinsic sensor, in that its basic function is simply to carry coherent light to the tip where the transduction process is initiated. Three basic designs have been developed to create a reflected light signal that can be related to the acoustic field. In the simplest approach, a bare fibre is cleaved to form a right circular cylinder. In the two other designs, an improvement in sensitivity comparable to piezoelectric polymer **hydrophones** can be achieved by treating the fibre tip, but at the cost of design simplicity and replacement ease. In choosing optic **hydrophones** the following points are of concern.

a) Refractive index change type **hydrophones**, for example fibre tip [39].

   In the simplest approach, light from a laser diode is coupled to a multi-mode fibre with a bare end face. To a good approximation, the light is reflected according to the Fresnel intensity reflection coefficient, $R = [(n_c - n_w)/(n_c + n_w)]^2$, where n_c and n_w are the indices of ~~reflection~~ refraction of the fibre core and water, respectively. Pressure variations in the acoustic wave cause a change in density, which in turn alters the refractive indices, and thus the reflected light intensity. A minimum detectable pressure of 0,5 MPa has been achieved, but this level could possibly be reduced by using signal averaging in cases of repetitive signals, high light source powers or very sensitive photodetectors. The fibre tip has a high damage threshold, but should it be damaged by cavitation, the fibre can be recut without affecting sensitivity. After cleaving, the reflected amplitudes in water and, if possible, in air need to be confirmed to be the same as before damage in order to assure that the sensitivity has not changed. Ideally a check with a reference source of known (sub-damage) output should be performed [12]. An alternative implementation of the refractive change type **hydrophone** uses a thick glass block instead of the fibre tip [48], [49]. Such a device can possibly provide a better low frequency limit in comparison to the diffraction limited fibre-optic version, which is likely to affect the peak rarefactional pressure part of the waveforms determined [50].

b) Two-beam interferometer [51], [52], [53].

   To increase measurement sensitivity, the fibre tip can be mirrored and incorporated into the measuring arm of a two-beam interferometer. The optical phase change caused by the tip movement results in a signal proportional to the acoustic displacement or, when a heterodyne technique is used, the particle velocity, both of which lead to a calculation of the pressure.

c) Fabry-Perot interferometer [54], [55], [56], [57], [58], [59], [60].

As an alternative to the optical complexity of two-beam interferometry, but still with improved sensitivity compared to the bare fibre design, a Fabry-Perot (FP) interferometer can be formed by attaching an FP cavity to the end of the fibre. When light is sent down the fibre, optical reflections occur at the interfaces between the fibre and the cavity, and the cavity and the load (water). The optical reflection coefficients are determined either by the Fresnel formula for uncoated cavity surfaces or by the type and thickness of metal coatings on these faces.

Various sources of distortions have been noted in fibre-optic **hydrophones** and several methods to analyse and compensate for these effects have been studied [61], [62], [63], [64].

In addition to the fibre-optic versions, Fabry-Perot interferometer type **hydrophones** with plane substrates have also been constructed. Advantages of such sensor designs are the possible use as array sensors [65], [66] and the exclusion of acoustic resonance and diffraction effects of the fibre body from the frequency response [67].

B.9.5 Relative performance of different types

The choice of a particular type of **hydrophone** for a specific task will depend on a number of factors. As there is a large variety of designs of **hydrophones** of all basic constructional types, it is not possible to produce simple guidelines for choosing the most appropriate one. However, the following points are worth noting.

a) A membrane **hydrophone** will exhibit less variation in its frequency response than a needle **hydrophone**.
b) The sensitivity of a **hydrophone** with a ceramic active element will usually be higher than one with the same diameter active element made from PVDF.
c) In the case of membrane **hydrophones**, the membrane constitutes a large, plane obstacle of finite reflectivity in the ultrasonic field. The reflected part of the ultrasonic wave might return in a coherent way to the **ultrasonic transducer** and react on it by acoustic interference [68]. This is particularly important in continuous wave excitation of **ultrasonic transducers**, and this source of error should be kept in mind, although its effect on measurements can usually be minimized. In all types of needle **hydrophone**, the effect of reflections is present but to a smaller extent.

B.10 Typical specification data for hydrophones

Examples of typical properties of certain **hydrophone** types are given in Table B.1.

Table B.1 – Typical specification data for hydrophones, in this case given at 1 MHz [69]

Hydrophone type	End-of-cable loaded sensitivity (with a specified load Z_L) ~~$M_L(f)$~~ $M_L(f)$ µV/Pa	Electric load resistance and parallel capacitance (specified load)	Cable length m	End-of-cable capacitance C or End of cable resistance and parallel capacitance	End-of-cable open-circuit sensitivity $M_c(f)$ µV/Pa
PVDF needle 1 mm diameter	0,100	1 MΩ 30 pF	1	130 pF	0,123
PVDF needle 0,6 mm diameter	0,032	1 MΩ 30 pF	1	130 pF	0,039
PVDF membrane 1 mm diameter	0,098	50 kΩ 5 pF	0,7	8,9 Ω 128 pF	0,102
PVDF membrane 0,5 mm diameter	0,033	50 kΩ 5 pF	0,7	12 kΩ 97 pF	0,035
Ceramic needle 1 mm diameter	0,56	1 MΩ 30 pF	1	150 pF	0,67

Annex C
(informative)

Acoustic pressure and intensity

Traditionally, ultrasonic fields have been characterized by the parameter of intensity and this is appropriate and directly relevant for many applications.

However, the **instantaneous intensity** $I(t)$ may be given by

$$I(t) = p(t)\ v(t) \tag{C.1}$$

where

$p(t)$ is the **instantaneous acoustic pressure**;

$v(t)$ is the particle velocity.

Under conditions of plane progressive waves, the **instantaneous intensity** is given by either Formula (C.2) or Formula (C.3):

$$I(t) = p(t)^2/\rho c \tag{C.2}$$

$$I(t) = \rho c\ v(t)^2 \tag{C.3}$$

These expressions have only limited validity and cannot generally be applied throughout an acoustic field. However, Formula (C.2) is almost exclusively used to derive **instantaneous intensity** from **hydrophone** measurements of **instantaneous acoustic pressure**.

To illustrate the significance of this, it can be shown (see [70]), for example, that the ratio of the true intensity to the plane wave approximation value is 0,66 at a distance of 5 mm from the face of a circular plane piston **ultrasonic transducer** of diameter 30 mm and in continuous wave operation. At a distance equal to the diameter of the **ultrasonic transducer**, the ratio is about 0,94.

It is for these reasons that this document recommends the specification of acoustic pressure parameters and, as such, these are the measured parameters appropriate to any acoustic field.

For the determination of derived intensity from acoustic pressure, the values of ρ, c and ρc for distilled or de-ionized water, as a function of temperature, given in Table C.1, may be used.

Unlike peak pressure parameters, derived intensity data do not depend on phase data of the pressure spectra due to the quadrature of the pressure data and Parseval's theorem [36]. Thus, for the determination of derived intensity from acoustic pressure using waveform deconvolution (see Annex D), phase response data of the **hydrophone** is not required, e.g. a constant phase of zero versus frequency can also be used.

Table C.1 – Properties of distilled or de-ionized water as a function of temperature [71]

Temperature	Density of the water	Speed of sound in the water	Characteristic acoustic impedance
T	ρ	c	ρc
°C	10^3 kg/m^3	m/s	10^6 kg/m^2/s
16	0,998 9	1 469,4	1,467 8
18	0,998 6	1 476,0	1,473 9
20	0,998 2	1 482,3	1,479 6
22	0,997 8	1 488,3	1,485 0
24	0,997 3	1 494,0	1,490 0
26	0,996 8	1 499,3	1,494 5
28	0,996 2	1 504,4	1,498 7

Annex D
(informative)

Voltage to pressure conversion

D.1 General

The relationship between the pressure experienced by a **hydrophone** and the voltage it produces at its output is related through the **end-of-cable loaded sensitivity** of a **hydrophone**, and often the **end-of-cable loaded sensitivity** of a **hydrophone** will have been determined over a wide frequency range. This document provides a method to convert the measured end-of-cable voltage $u_L(t)$ produced by the **hydrophone** back to an **instantaneous acoustic pressure** $p(t)$ according to Formula (D.1):

$$\sout{p(t) = u_L(t) / M_L(f_{awf})} \quad p(t) = u_L(t) / |\underline{M}_L(f_{awf})| \tag{D.1}$$

if the frequency response of the **hydrophone** meets the criteria in 5.1.7.1 and

$$\sout{p(t) = \Im^{-1}[U_L(f) / M_L(f)]} \quad p(t) = \mathcal{F}^{-1}[\underline{U}_L(f) / \underline{M}_L(f)] \tag{D.2}$$

otherwise (see 5.1.2).

The rationale behind this approach is that Formula (D.1) is only valid if:

– the acoustic field generated by the **ultrasonic transducer** has a very narrow frequency **bandwidth**, or

– the **end-of-cable loaded sensitivity** of the **hydrophone** across the **bandwidth** of the **hydrophone** does not vary significantly from the **end-of-cable loaded sensitivity** measured at the **acoustic-working frequency**.

In all other cases, the frequency response of the **hydrophone** ~~should be~~ is deconvolved from the end-of-cable voltage using Formula (D.2). These requirements contribute to the **bandwidth** specifications of 5.1.7.2.

The **end-of-cable loaded sensitivity**, $\underline{M}_L(f)$, is a complex-valued quantity ~~and~~ but it has historically been supplied as a magnitude-only quantity. However, there are now several national standards and other laboratories capable of measuring the phase response of **hydrophones** in broad frequency ranges, and the deconvolution process ~~of equation D.2~~ according to Formula (D.2) can ~~also~~ make use of this additional data. See [17], [18], [34], [35], [36], [72], [73].

An alternative approach to measuring **hydrophone** phase response is the computation of phase response data from modulus response data. A minimum phase system can be assumed for some **hydrophones**, which allows an estimation of the frequency-dependent phase response using, for example, Hilbert-Transform methods or iterative phase signal reconstruction techniques [73], [74], [75].

A straightforward easy-to-implement method of calculating the discrete phase response data $\arg\underline{M}(f_m)$ in rad from modulus response data for minimum phase systems is provided by the Bode gain-phase relation formulation [76], which can be written here as Formula (D.3):

$$\arg \underline{M}\left(f_m\right) = \frac{2 f_m}{\pi} \sum_{n=0}^{N/2} \frac{\ln\left(\left|\underline{M}\left(f_n\right)\right| / \left|\underline{M}\left(f_m\right)\right|\right)}{f_n^2 - f_m^2} \cdot \Delta f \qquad \text{(D.3)}$$

where n and m run from 0 to $N/2$, $n \neq m$, N denotes the number of time signal data points (resulting in $N/2 + 1$ frequency domain data points in the single-sided spectrum, see Clause D.3), f_n and f_m denote discrete frequencies, and Δf is the constant frequency increment, e.g. $\Delta f = f_{n+1} - f_n$.

NOTE Depending on the sign convention of the Fourier transformation algorithm used, the phase response calculated with Formula (D.3) possibly needs to be inverted, e.g. needs to be multiplied with −1. A wrong sign will lead to waveforms obscured during deconvolution showing non-physical additional oscillations and, thus, can easily be spotted in a test application.

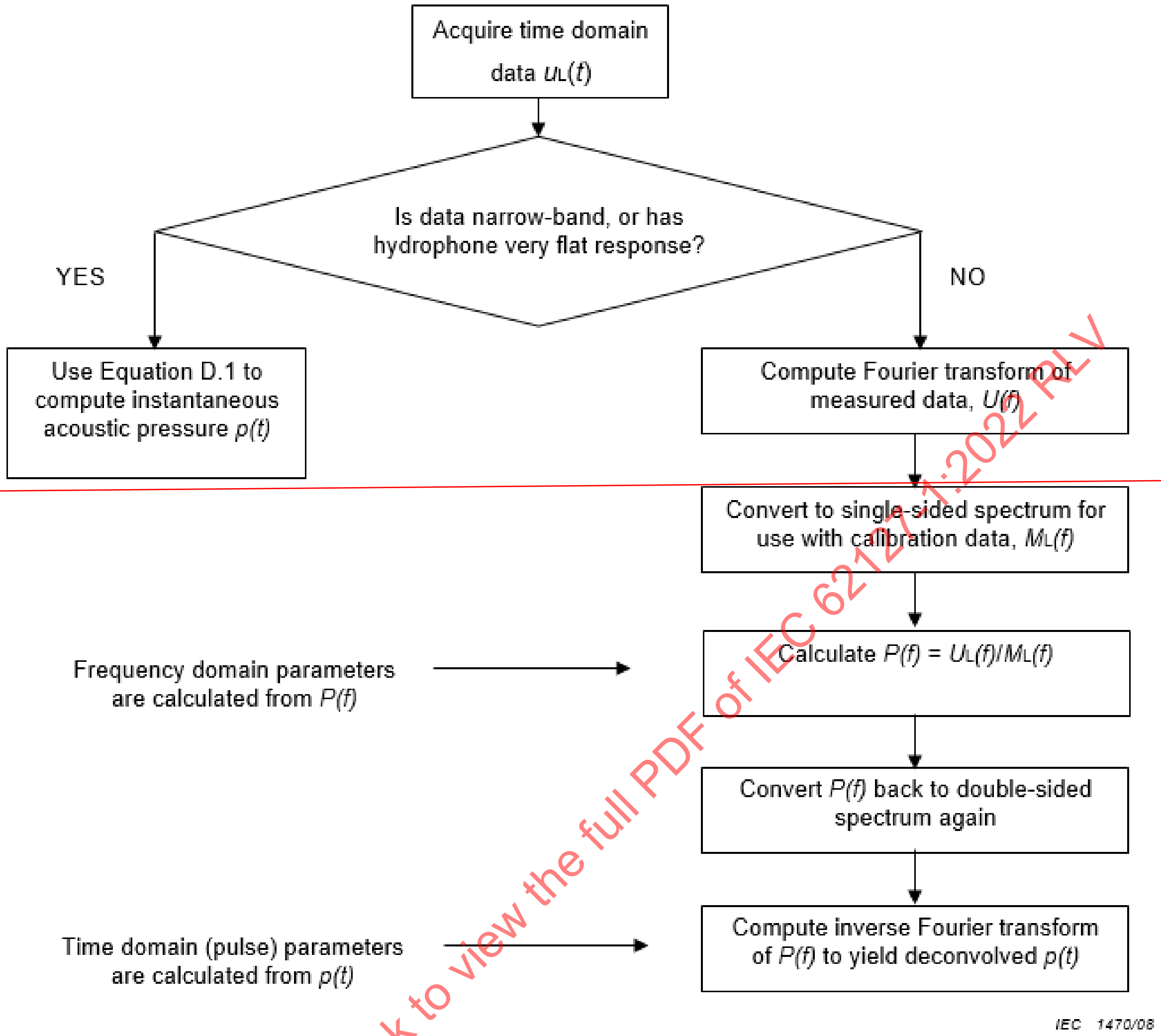
The methods of phase calculation from modulus responses may also be helpful when used in combination with measured **hydrophone** phase data to correct the phase calibration data for linear-with-frequency terms by this comparison. Furthermore, it may be used to adequately extrapolate the measured data below and above the experimentally available frequency ranges by assuming reasonable modulus data for those frequency ranges first, see D.4.2, and then calculating the suitable phase response extrapolation with Formula (D.3). An application example for this method is described in [19].

A calculation scheme including step-by-step guidance and examples can be found in a deconvolution tutorial available through online publication [77]. The tutorial uses freeware software tools only and comprises all necessary procedures for deconvolution and associated **uncertainty** estimation[3].

D.2 Hydrophone deconvolution procedure

The complete process for deconvolving the full frequency response of a **hydrophone** according to Formula (D.2) is shown as a flow diagram in Figure D.1.

3 This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.


Acquire time domain data uL(t)
Is data narrow-band, or has hydrophone very flat response?
YES
NO
Use Equation D.1 to compute instantaneous acoustic pressure p(t)
Compute Fourier transform of measured data, U(f)
Convert to single-sided spectrum for use with calibration data, ML(f)
Frequency domain parameters are calculated from P(f)
Calculate P(f) = UL(f)/ML(f)
Convert P(f) back to double-sided spectrum again
Time domain (pulse) parameters are calculated from p(t)
Compute inverse Fourier transform of P(f) to yield deconvolved p(t)
IEC 1470/08

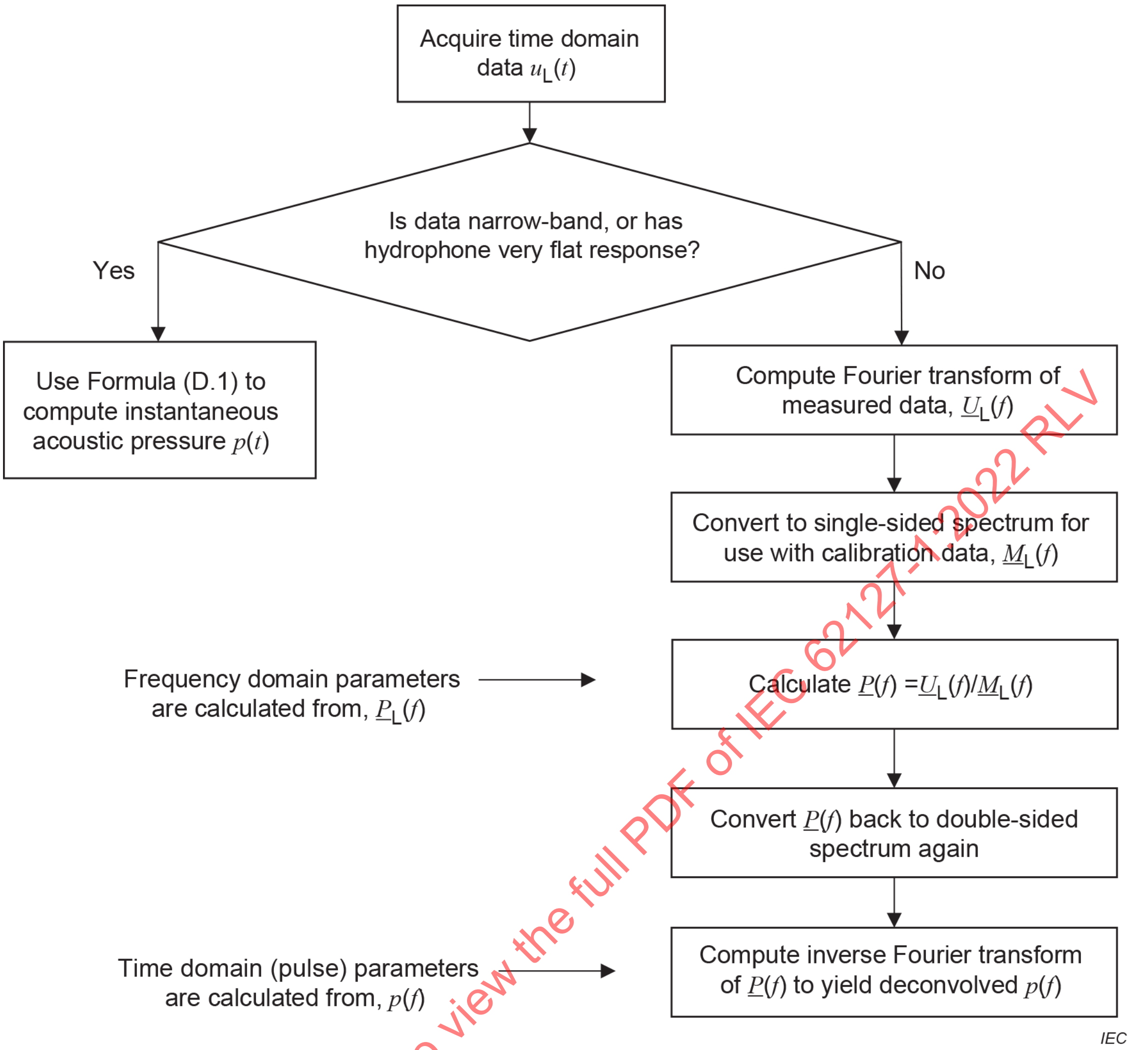


Figure D.1 – A flow diagram of the hydrophone deconvolution process

D.3 Converting the data between double-sided and single-sided spectra

Hydrophone calibration data is typically provided over a range of positive frequency values, whereas conventional fast Fourier transform routines output zero-centred frequency data, with both positive and negative frequency components. Due to the symmetry of the frequency spectrum, the conversion to a single-sided frequency spectrum (containing only positive frequencies) for use in the **hydrophone** deconvolution process should be trivial. In fact, often users are only presented with a single-sided spectrum and may be unaware of the double-sided nature of the original frequency spectra. Unfortunately, several commercial Fourier transform routines do not accomplish this process accurately. A brief description of both the problem and its remedy follows.

Consider a set of data sampled at frequency f_s, and thus having a Nyquist frequency, ~~$f_N = f_s/2$~~ $f_{Nyquist} = f_s/2$. A typical Fast Fourier Transform (FFT) algorithm will return points ordered such that the first point has frequency f_0 then f_1, f_2, … up to ~~f_N~~ $f_{Nyquist}$. The next point is at ~~$-f_{N-1}$~~ $-f_{Nyquist-1}$ and then ~~$-f_{N-2}$, $-f_{N-3}$~~ $-f_{Nyquist-2}$, $-f_{Nyquist-3}$. For all components other than frequency 0 (i.e. DC), the ~~amplitudes~~ moduli of the positive and negative frequency points are equal, and the single-sided spectrum can be obtained by simply doubling the amplitude of all non-DC components. The complex values of corresponding positive and negative frequency points of the same modulus are complex conjugates. A thorough discussion of the computational issues associated with the Fourier transform is provided by [78].

The problem seen with some commercial routines that conduct the double-sided to single-sided conversion is that they simply halve the size of the data array and double the amplitudes of all but the first component. This is an incorrect method because for a trace of N data points (N being an even positive number), the DC signal is the first data point, with the positive frequencies occupying the next $N/2$ locations in the array. Thus, the data at the (highly important) Nyquist frequency are at location $N/2 + 1$. However, the above method of simply extracting the first half of the data sequence has discarded this point. Failure to include the Nyquist frequency data point will introduce errors and will prevent the inverse Fourier transform process from working properly, as well as introducing significant phase errors. Table D.1 shows the correct method of conducting this conversion.

Table D.1 – Method of conversion from a double- to a single-sided spectrum

Double-sided spectrum Number of points = N Data array = $DS[1..N]$	**Single-sided spectrum** Number of points = $N/2 + 1$ Data array = $SS[1..N/2 + 1]$
$DS[1]$	$SS[1] = DS[1]$
$DS[2]$	$SS[2] = 2 \cdot DS[2]$
$DS[3]$	$SS[3] = 2 \cdot DS[3]$
..	..
$DS[N/2]$	$SS[N/2] = 2 \cdot DS[N/2]$
$DS[N/2 + 1]$ at the Nyquist frequency	$SS[N/2 + 1] = DS[N/2 + 1]$
$DS[N/2 + 2]$	Discard
.. $DS[N]$	.. Discard

Similar care should be taken when converting single-sided spectra back to double-sided spectra for the inverse Fourier transform operation since data points at frequency 0 (DC) and frequency $N/2 + 1$ (Nyquist frequency) appear only once in a double-sided spectrum, whereas all other components appear twice as complex-conjugated values (as both positive and negative frequency components). Table D.2 shows the correct method of converting from a single-sided spectrum back to a double-sided spectrum. SS^* denotes the complex conjugate of SS.

Table D.2 – Method of conversion from a single- to a double-sided spectrum

Single-sided spectrum Number of points = $N/2 + 1$ Data array = $SS[1..N/2 + 1]$	**Double-sided spectrum** Number of points = N Data array = $DS[1..N]$
$SS[1]$	$DS[1] = SS[1]$
$SS[2]$	$DS[2] = SS[2]/2$
$SS[3]$	$DS[3] = SS[3]/2$
..	..
$SS[N/2]$	$DS[N/2] = SS[N/2]/2$
$SS[N/2 + 1]$	$DS[N/2 + 1] = SS[N/2 + 1]$
	$DS[N/2 + 2] = SS^*[N/2]/2$
	$DS[N/2 + 3] = SS^*[N/2 - 1]/2$
	..
	$DS[N] = SS^*[2]/2$

D.4 Use of hydrophone calibration data

D.4.1 Calibration data interpolation

The combination of sampling interval (time increment: Δt) and number of points N acquired determines the frequency interval (frequency increment: Δf) of the spectrum of the measured signal according to Formula (D.4):

~~Frequency increment = 1,0/(time increment x number of points)~~

$$\Delta f = \frac{1}{\Delta t \times N} \quad \text{(D.4)}$$

Frequently, it is found that this frequency increment of the measured data differs from that supplied between consecutive points in the **hydrophone** calibration data. To ensure that calibration data is available at the appropriate frequency points, it may be necessary to interpolate values at the required spacing from the calibration data. Cubic or Bezier spline interpolation routines have been found to be an effective means of providing this additional interpolated data [18]. One of the advantages of these methods is that the interpolation function only needs to be pre-computed once. The interpolation function can then be used to produce calibration data at any required frequency increment. Thus, a refined frequency response curve for each **hydrophone** can be pre-calculated and stored for later use. Alternatively, if **hydrophone** calibration data stem from pulse excitation measurement via Fourier transform, the frequency increment of the data can be adjusted to the application needs by the choice or modification of the signal length in time, e.g. the sample rate and number of data points, within the pulse calibration measurements [34], [35], [36]. For a given sample rate as used in the calibration measurement which determines the maximum frequency (Nyquist frequency), the number of data points may be altered by zero padding afterwards to modify the frequency increment appropriately.

~~In addition, hydrophone calibration data needs to be extrapolated towards high frequencies. An appropriate sampling rate of, for instance, 500 MS/s leads to a Nyquist frequency of 250 MHz. Hydrophone calibration data is needed up to this frequency for the deconvolution calculation (see Clause D.3). The calibration data extrapolation needs to be performed in a way that additional high frequency noise in the deconvolved waveforms is avoided. Such noise can arise from low hydrophone sensitivity (at high frequencies) and from the Gibbs phenomenon. Appropriate suppression may be achieved by low-pass filtering of the pressure pulse spectrum prior to the back transformation to the time domain and should be controlled by comparison of high frequency noise in the deconvolved and in the undeconvolved waveform (Figure D.2).~~

D.4.2 Calibration data extrapolation

For the deconvolution calculation according to Formula (11) or (16), the data sets of the voltage spectrum $\underline{U}_{\mathrm{L}}(f)$ and the sensitivity $\underline{M}_{\mathrm{L}}(f)$ need to cover the same frequency ranges from zero to the Nyquist frequency of the **hydrophone** measurement. For instance, for a typical waveform sampling rate of 500 MS/s (mega-samples per second), data is needed up to 250 MHz. Therefore, extrapolation of $\underline{M}_{\mathrm{L}}(f)$ may be used to cover frequencies f outside the calibration range available if necessary. However, requirements for the frequency range covered by experimental **hydrophone** calibrations are specified in 5.1.7.2.2 to be at minimum from below half of the **acoustic-working frequency** up to four times the **acoustic-working frequency** to ensure that the major portion of the pressure spectrum is evaluated using most reliably confirmed sensitivity data on the one hand, and to allow the application of the method and standard to most applications in practise, where **acoustic-working frequencies** may extend up to 25 MHz and available calibration ranges may reach up to 100 MHz, on the other hand. For **acoustic-working frequencies** larger than 25 MHz, the acceptable upper experimental calibration data limit of 100 MHz can still be retained for practical reasons. For high intensity therapeutic ultrasonic fields usually comprising **acoustic-working frequencies** below 5 MHz, the range opened for extrapolation is reduced in 8.3.2 to beyond 20 f_{awf} because spectra at clinical driving levels comprise far more higher harmonics.

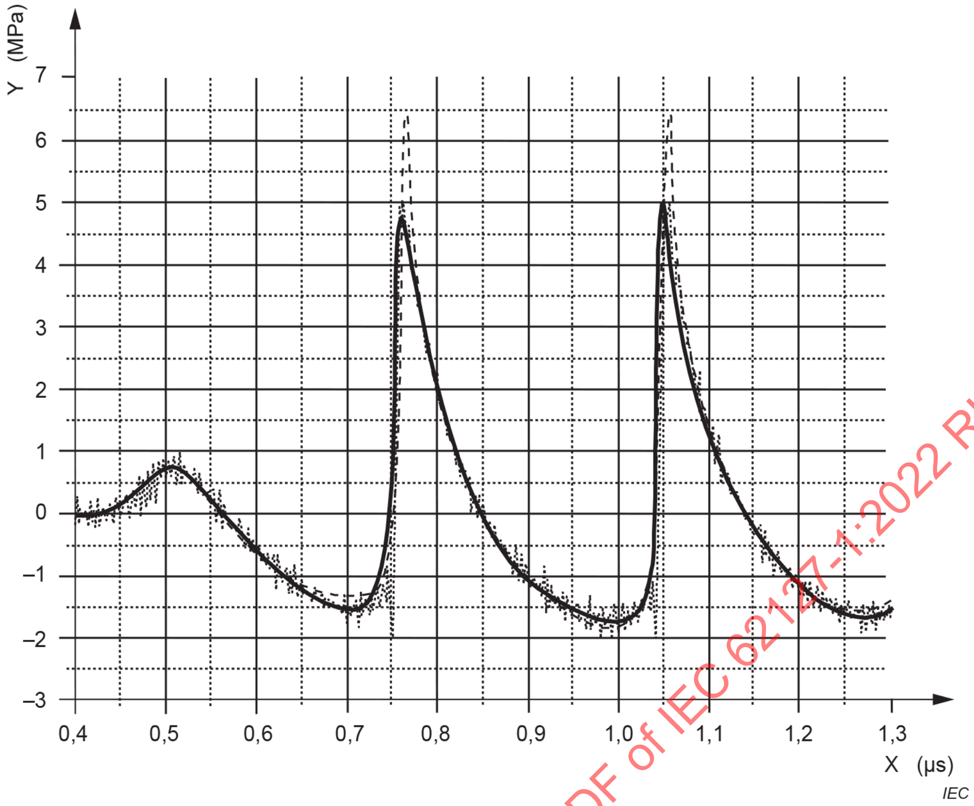
A convenient way may be to start with extrapolating the modulus data first and to adjust the phase data in a second step using Formula (D.3). This will assure consistent complex-valued response extrapolation, including the phase value being zero at zero frequency as is necessary for any real-valued time domain impulse response [20]. The modulus extrapolation should follow the trend indicated by the calibration range limit region; for instance, if some thickness mode resonance behaviour can be observed at the high frequency end a decreasing behaviour with frequency may be estimated from that. Of course, the sensitivity cannot become zero. This would induce singularities in the deconvolution because some noise can be expected in the voltage spectrum even at frequencies not transduced by the **hydrophone** due to zero sensitivity.

Several investigations have shown that rather simple extrapolation schemes work well for most applications, e.g. lead to reasonable deconvolved waveform results. For membrane **hydrophones**, using the lowest calibration data point modulus as constant value down to zero and using the highest calibration data point modulus as constant value above the calibration range may be sufficient [17], [19], [20] and can be applied as standard procedure. However, if the preamplifier is known to cause a significant roll-off at low frequencies, either from manufacturer's specifications or from electrical measurements, such sensitivity decrease should be accounted for in obtaining $\underline{M}_L(f)$. In this case, the extrapolation should include the constant value extrapolation combined with the preamplifier's relative response from the lowest calibration frequency down to $f_{awf}/16$ (see 5.1.7.1, NOTE 3). From zero frequency to $f_{awf}/16$, $\underline{M}_L(f)$ can be assumed to equal the value at $f_{awf}/16$. For needle type and fibre-optic **hydrophones**, a decreasing sensitivity towards low frequencies can be expected due to the impact of diffraction at the sensor tip. Here, decreasing sensitivity modulus functions show good results and should be applied [18], [79]. If available, more comprehensive **hydrophone** frequency response modelling may be used for the purpose of extrapolation. Relatively simple secondary impulse calibration methods [11], [12] can also be applied by the hydrophone user to extrapolate sensitivity data reasonably, as can measurements of similar units of the same design (see 5.1.7.2.2, NOTE 2 and NOTE 3).

The **uncertainty** introduced to the measurement by extrapolating the calibration data can be assessed together with the regularization error (see D.4.3) using an upper bound function estimation method for the pressure spectrum [14].

D.4.3 Regularization filtering

Mathematically speaking deconvolution is an ill-posed inverse problem [13], [14]. To avoid excessive additional high frequency noise in the deconvolved waveforms, regularization filtering may be necessary. Such noise can arise from low **hydrophone** sensitivity (at high frequencies) and from the Gibbs phenomenon. Appropriate suppression may be achieved by low-pass filtering of the pressure pulse spectrum prior to the back transformation to the time domain. Figure D.2 shows an example waveform obtained in Doppler mode of a diagnostic ultrasound machine with voltage to pressure conversion using narrow-band approximation, deconvolution, and deconvolution with additional low-pass filtering in comparison. Deconvolution removes the strong overshoot of the waveform in the peak compressional parts of the wave obtained when using the narrow-band approximation and caused by the **hydrophone** thickness mode resonance at high frequencies. However, the deconvolution also introduces high frequency noise and artificial rarefactional pressure peaks in front of the steep pressure steps (Gibbs oscillations). Using the additional regularization filtering, the additional noise and high frequency oscillations are appropriately removed. On the other hand, any additional low-pass filtering causes additional effective limitations of the detection **bandwidth** and, in particular, peak compressional parts of nonlinearly distorted ultrasonic waveforms incorporating high frequency components may possibly be cut. Requirements for the filtering are provided in 5.1.7.2 including guidance on how to include in the **uncertainty** analysis the systematic error introduced through regularization for parameters derived from the deconvolved **acoustic pulse waveforms** [14], [21].



Key

X time

Y pressure

NOTE The example shows part of a Doppler pulse measured by a needle hydrophone. The voltage to pressure conversion uses (--) $M_L(f_{awf})$ (dashed line) $M_L(f_{awf})$, (···) using deconvolution $M_L(f)$ $M_L(f)$, and (—) (solid line) deconvolution with additional low-pass filtering (−6 dB at 80 MHz).

Figure D.2 – Example of waveform deconvolution

D.5 Implication of the hydrophone deconvolution process on measurement duration

Many acoustic reporting parameters require that a **hydrophone** will have been scanned through the acoustic field, and these measurements can be time-consuming. Figure D.2 tends to suggest a significant increase in the measurement time overhead. However, if implemented correctly, this process does not add any significant increase to the total measurement duration.

The majority of automated scanned **hydrophone** acquisition systems are PC-controlled, and, although digital oscilloscopes have a range of on-board processing capabilities, much of the data post processing is done by PC. The key to ensuring the deconvolution is a time effective process to ensure that the processing of data transfer to the PC is done while the **hydrophone** is being moved to its next location within the acoustic field. Once the data is on the PC, the remainder of the deconvolution process (two Fourier transforms and a division) can be done rapidly. In fact, with efficient implementation, the processing can be done fast enough to give real-time feedback of deconvolved waveforms to the user, which can in turn lead to better alignment on spatial-peak features within the acoustic field.

D.6 Validation of deconvolution implementation

There are several possibilities to validate the correct implementation of the numerical deconvolution procedure. The validation should be performed using example measurement data of a broadband pulse. First of all, the waveforms obtained using the deconvolution should be compared with those using the narrow-band assumption on the same **hydrophone** voltage data. If the implementation comprises major errors like, for instance, a wrong sign in the phase term of the Fourier transform algorithm, this can be observed easily through the appearance of unexpected waveforms with extra oscillations that physically make no sense. For typical waveforms and **hydrophones**, only slight differences would be expected in the rarefactional parts of waveforms, and typical overshoots in the compressional parts should be removed by the deconvolution. Other computational errors often result in significant time-shifts or inversion of the signal, all of which are also easily spotted through such comparisons.

The second method of validation of the implementation is to use a broadband **hydrophone** with flat frequency response for comparison measurement of a typical broadband pulse waveform. Membrane **hydrophones** with foil thicknesses from 4,5 µm to about 12 µm are available that provide very flat frequency responses up to 70 MHz and beyond and can be applied as reference.

Finally, a pulse check source or a reference transducer system for which waveforms have already been measured with a broadband **hydrophone** or using already validated deconvolution can be applied for validation. Metrology institutes and measurement equipment manufacturers may offer corresponding waveform measurement services for such reference transducer systems.

A publicly available deconvolution tutorial including stored example reference data sets for **hydrophone** calibration data, **hydrophone** signal voltage data, and corresponding deconvolved pressure waveforms including **uncertainty** estimates is available [77] and can be used for validation of custom made numerical implementations[4].

[4] This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

Annex E
(informative)

Correction for spatial averaging

E.1 Linear and quasilinear fields

For most measurements made on diagnostic ultrasonic fields, the diameter of the active element of the **hydrophone** is comparable with the width of the ultrasonic beam and the **hydrophone** measures the average acoustic pressure over the area of its active element rather than the pressure at the centre of its active element. The difference depends on the spatial variation of the ultrasonic field. To correct for this spatial averaging effect, a simple method has been developed [80], [81], which utilizes beam-plots obtained with a step size equal to one **hydrophone** ~~radius~~ **size**. A number of other similar methods can also be applied [37], [38], [82], [83], [84], [85].

The procedure for determining corrections makes the following assumptions.

a) The **hydrophone** output is proportional to the acoustic pressure averaged over its active element, which is assumed to be a circular area having a radius equal to the geometrical radius.

b) The radial field distribution, usually in the focal plane of the transducer, from the axial peak to a distance equal to the radius of the active element of the **hydrophone**, can be modelled by a quadratic function: $p(r) = 1 - \mathrm{b}r^2$ where b is a constant. The limits on the accuracy of this correction are determined by assuming that the true beam shape is described by a Bessel function:

$$p(r) = \frac{2\mathrm{J}_1(kar/d)}{(kar/d)} \tag{E.1}$$

where

k is the circular wave number;

a is the transducer radius;

r is the distance from the axis in the focal plane;

d is the focal distance;

J_1 is the Bessel function of the first kind, of order 1.

c) The correction procedure for a sawtooth waveform (one distorted by nonlinear propagation) is not the same.

Under these assumptions, the correction factor, K_{sa}, at the centre of the beam is:

$$K_{\mathrm{sa}} = (3 - \beta)/2 \tag{E.2}$$

where

β is the signal at one **hydrophone** radius from the axis divided by the signal on axis.

The correction should be based on the average value of ~~δ~~ β determined in two perpendicular oriented directions.

~~NOTE 1 Signal represents p_+, p_- or $ppsi^{1/2}$. For each of these quantities a different K_{sa} may be expected. The correction factor for intensity related values derived from $ppsi$ is given by the square of K_{sa} for $ppsi^{1/2}$.~~

~~NOTE 2 In a number of cases, the $ppsi^{1/2}$ is replaced by any linearly related quantity, e.g.: in the case of a continuous wave signal the term $ppsi^{1/2}$ is replaced by **rms acoustic pressure.**~~

This formula is obtained by convolving the response of the **hydrophone** with the assumed true field profile for the two measurement positions and relating β to the ratio of the true pressure to the measured value on axis. The procedure for determining the correction $\delta = (K_{sa} - 1)$ is valid for $\beta > 0{,}8$; this corresponds to using a **hydrophone** with a radius that is less than 0,6 times the −6 dB beam radius. For currently available **hydrophones** with 0,5 mm diameter active elements, the correction is less than 10 % provided that the −6 dB beam radius is greater than 0,4 mm.

Because this correction method might not be valid in the case of sawtooth waveforms (i.e. distorted by nonlinear propagation) another formula may be more valid [81].

The correction factor, K'_{sa}, at the centre of the beam is:

$$K'_{sa} = (3 - 2\,\beta') \qquad \text{(E.3)}$$

where

β' is the signal at half a **hydrophone** radius from the axis divided by the signal on axis.

The correction should be based on the average value of ~~δ'~~ β' determined in two perpendicular oriented directions.

NOTE 1 "Signal" in the above definitions of β and β' represents ~~p_+, p~~ p_c, p_r or $ppsi^{1/2}$. For each of these quantities a different K_{sa} or K'_{sa} ~~may~~ can be expected. The correction factor for intensity related values derived from $ppsi$ is given by the square of ~~K'_{sa} for~~ K_{sa} or K'_{sa}, where these are derived using $ppsi^{1/2}$.

NOTE 2 In a number of cases, the $ppsi^{1/2}$ is replaced by any linearly related quantity, e.g. in the case of a continuous wave signal the term $ppsi^{1/2}$ is replaced by **RMS acoustic pressure.**

The **uncertainty** of the correction $\delta' = (K'_{sa} - 1)$ is estimated to be 10 % for $\beta' > 0{,}92$.

NOTE 3 The overall **uncertainty** can also depend on the actual (not necessarily symmetric) geometry of the **hydrophone's** active element.

~~It should be noted~~ Note that the effective diameter of well-designed PVDF needle **hydrophones** is readily predictable. For membrane **hydrophones**, the response is more complicated and, in some cases, and at low frequencies, the geometrical radius of the membrane **hydrophone** might not be equal to the **effective hydrophone** ~~**radius**~~ **size** as determined from directional response measurements (see [42]). In this case, the procedure is modified by moving the **hydrophone** by its effective radius instead of its geometrical radius.

Experimental results using a number of **hydrophones** of different size of active element [31] showed that for most focused ultrasonic fields the procedure given above underestimates the correction. Other studies [86] have shown that the major reason for the underestimates is the residual presence of nonlinear distortion in the fields.

Studies have shown [86] that, providing ~~σ_m~~ $\delta_m < 0{,}5$, the correction procedure given above will provide reasonable estimates of the spatial averaging correction for all acoustical parameters within **uncertainties** of 10 % to 15 %. For more distorted waveforms, it is possible to delineate the following regimes for estimation of spatial averaging corrections in terms of the parameter

R_{bh}, the ratio of the −6 dB **beamwidth** to the effective **hydrophone** diameter. Guidance for the magnitude of the likely corrections for the **peak-compressional acoustic pressure** p_c, **peak-rarefactional acoustic pressure** p_r, and **pulse-pressure-squared integral** $ppsi$, are as follows [86]:

$$R_{bh} > 2$$

NOTE 4 The referenced study used the nonlinear propagation parameter σ_m for characterizing the amount of nonlinear distortion. However, IEC 62127-1:2007/AMD1:2013 changed to using the **local distortion parameter** σ_q instead. In typical applications both parameters have similar values. Therefore, for the purpose of the estimates here, σ_m can be replaced by σ_q.

For 0,5 < σ_m < 1,5 the maximum p_c and p_r corrections will be approximately 13 %, with the correction to $ppsi$ being less than 25 %; for σ_m > 1,5, the peak pressure corrections will be higher but are unlikely to exceed 20 %.

$$1,5 \leq R_{bh} \leq 2$$

For σ_m < 1,5, the corrections to p_c and p_r will be less than 20 % while the correction to $ppsi$ will generally not exceed 40 %. For higher σ_m values, corrections to p_c, p_r and $ppsi$ can be greater than 30 %, 20 % and 50 %, respectively.

$$R_{bh} < 1,5$$

In this regime, large spatial averaging effects occur for all parameters but particularly for p_c and p_r at all values of σ_m, corrections for p_r can reach 50 % but these are not significantly different from the values obtained from the procedures given above. In contrast, p_c corrections can be of the order of 100 % for 0,5 < σ_m < 1,5, and for σ_m > 2 can be in excess of 200 % corresponding to $ppsi$ corrections of 300 %. Therefore, in situations where R_{bh} < 1,5, it is important that a smaller **hydrophone** be used for measurements.

E.2 Linear fields, quasilinear fields, and broadband nonlinearly distorted waveforms

An inverse spectral filtering approach may be used to correct for spatial averaging effects for linear beams or nonlinear beams that contain multiple harmonics of the fundamental frequency. The inverse spectral filtering approach is more general than the method in Clause E.1. The method in Clause E.1 assumes linear propagation. The inverse spectral filtering approach allows for linear or nonlinear propagation. The two methods give similar results for the spatial averaging correction at fundamental frequency, as shown in Figures 3 to 5 in reference [87]. In addition, the inverse spectral filtering approach gives appropriate spatial averaging corrections at harmonic frequencies for nonlinearly distorted waveforms. Another advantage of the inverse spectral filtering approach is that it does not require a separate off-axis **hydrophone** measurement. The effects of spatial averaging can be described by a spatial averaging filter $\underline{S}(f)$, which gives the frequency domain ratio of the spatially averaged **hydrophone** output to the signal that would be measured by an ideal point **hydrophone**. The **hydrophone** spatiotemporal response is assumed to be separable into a product of spatial and temporal factors, and extending Formula (11) or (16), the actual acoustic pressure corrected for both the spatial averaging effect and the effects of varying sensitivity is then calculated from Formula (E.4):

$$p(t) = \mathcal{F}^{-1}\left(\underline{LP}(f) \cdot \frac{\underline{U}_{\mathrm{L}}(f)}{\underline{M}_{\mathrm{L}}(f) \cdot \underline{S}(f)} \right) \tag{E.4}$$

The spatial averaging filter at each harmonic frequency depends on the ratio of the frequency-dependent **effective hydrophone size** to the frequency-dependent harmonic **beamwidth**. For harmonics with Gaussian-shaped radial profiles and assuming constant phase of $S(f)$, it can be shown that the spatial averaging filter is given by [87], [88], [89]

$$S(nf_1) = \frac{1 - \exp\left(-\Omega_n{}^2\right)}{\Omega_n{}^2} \tag{E.5}$$

where f_1 is the fundamental frequency and n the harmonic number, and

$$\Omega_n{}^2 = \frac{a_{\mathrm{eff}}{}^2(nf_1)}{2\sigma_n{}^2}, \tag{E.6}$$

where $a_{\mathrm{eff}}(nf_1)$ is the frequency-dependent **effective hydrophone size** evaluated at fundamental and harmonic frequencies, and σ_n describes the harmonic **beamwidth** parameter for a harmonic with radial profile shaped like $\exp(-r^2/2\sigma_n{}^2)$; r is the radial coordinate.

The frequency-dependent radius $a_{\mathrm{eff}}(nf_1)$ can be evaluated from directivity measurements at multiple frequencies (IEC 62127-3:2007, 5.5 and 5.6). Alternatively, for needle or reflectance-based fibre-optic **hydrophones**, an experimentally-validated theoretical form for $a_{\mathrm{eff}}(nf_1)$ can be used [43], [87]. For membrane **hydrophones**, an empirical formula for $a_{\mathrm{eff}}(nf_1)$ can be used [34], [90].

The **beamwidth** parameter σ_n can be obtained from theory, simulation, or experiment. In many cases relevant to medical ultrasound (nonlinear distortion not too severe), the fundamental beam will be similar in shape to the prediction based on linear propagation theory. Then σ_1 can be obtained by fitting a Gaussian function to the theoretical diffraction pattern from a focused, circular source, which results in σ_1 = 1,93 $D/(k_1 a_{\mathrm{s}})$, where D is the radius of curvature or focal distance, $k_1 = 2\pi/\lambda_1$, λ_1 is the fundamental wavelength, and a_{s} is the radius of the source [87].

In many cases relevant to medical ultrasound, the dependence of harmonic **beamwidth** on harmonic number can be accurately approximated by a power law, $\sigma_n = \sigma_1/n^q$ [87], [91]. The value of the exponent q depends on the degree of nonlinearity of the pressure signal, which can be described by the **local distortion parameter** σ_q. Simulation and experiment suggest that for $\sigma_q < 6$, q can be approximated by q = 0,78 − 0,032σ_q [87]. This formula has been shown to be valid even for high intensity therapeutic ultrasound signals with **peak compressional acoustic pressures** up to 48 MPa [91].

The combined effects of frequency-dependent sensitivity and spatial averaging for needle and reflectance-based fibre-optic **hydrophones** have been illustrated in a 27-panel graphical guide that can be used as an aid in choosing an appropriate **hydrophone geometrical radius** for a given measurement task [87].

While the method in Clause E.1 provides the spatial averaging correction at the centre frequency of a linear, narrow-band waveform, the method in Clause E.2 provides the spatial averaging filter at the fundamental and harmonics for linear and nonlinear waveforms. The method of Clause E.2 has been validated in experiments using nonlinear tone bursts [88]. Though the method has been verified only for a burst wave, it is considered to still be useful for a pulse wave. For short pulses (only a few cycles or less in duration), simulation has been used to determine the spatial averaging filter to frequencies also between harmonics [92]. The spatial averaging correction factor has been found to oscillate with local minima at the fundamental and harmonics and local maxima midway between harmonics [36], [92]. For quasi-linear beams and for waveforms comprising only one nonlinearly distorted wave cycle (sawtooth-like cycle), the magnitude of the oscillation is small (< 10 %). For highly nonlinear waveforms with more than one distorted wave cycle, the oscillation is greater due to interference effects of the higher frequency components stemming from different parts of the waveform [92].

Annex F
(informative)

Acoustic output parameters for multi-mode medical ultrasonic fields in the absence of scan-frame synchronization

F.1 General

The earliest clinical ultrasound scanners used fixed-focus, single crystal transducers to generate the ultrasound field. This transducer was either held stationary (for A-mode or M-mode operation), or mechanically moved from side to side (for B-mode operation). The invention of phased, linear-arrays allowed the focusing to be electronically controlled and, for B-mode, scanning to be carried out electronically. Static Doppler (D-mode or PWD, pulsed wave Doppler) and colour-flow imaging (CF-mode) have also been introduced and available for 15 years or more. In the last few years, harmonic imaging, CT-imaging and 3-D imaging have all appeared. To further add to the plethora of output configurations, each of these modes can, in principle and often in reality, be combined with any other mode or combination of modes. And yet, prescribed measurement methods have not moved on. All the major national and international standards relating to measurement of acoustic output were published in 1993 or before and were largely formulated several years before that. The methods, which seemed adequate for the majority of purposes at the time, are now extremely time-consuming to carry out and often impossible. There is now a need to reconsider the existing parameter definitions and measurement methods and perhaps to develop new ones more appropriate to modern imaging equipment. This Annex F is meant to gain support for a new approach before putting parts into a normative text in future. It can be used in those cases where there does not exist a scan-frame repetition.

F.2 Current philosophy

The approach, or philosophy, behind existing measurement standards goes back to the origins of diagnostic ultrasound when the ultrasound field was generated by a single crystal of fixed geometry. The starting point is that a single type of ultrasound pulse – defined by its **acoustic frequency**, duration and focusing properties – is generated. Each pulse generated is of exactly the same type and is directed either along a single well-defined **beam axis** (in the case of unscanned A-mode, M-mode or D-mode) or along a series of distinct and well-defined axes (in the case of the scanned B-mode or CF-mode). Each of these modes is considered to be a distinct "discrete **operating mode**"; for scanned modes it is assumed that a repeating sequence of pulses will form a "scan-frame" and that each scan-frame will contain exactly the same number of pulses.

For simple discrete modes, this approach works well. For unscanned modes, measurements can be made with a **hydrophone** along the **beam axis** allowing a focal point to be located and a variety of acoustic parameters to be determined. The main basic parameters defined in this document or in IEC 61161 are listed in Table F.1.

Table F.1 – Main basic parameters defined in this document or in IEC 61161

p_c	Peak-compressional acoustic pressure
p_r	Peak-rarefactional acoustic pressure
f_{awf}	Acoustic-working frequency
t_d	Pulse duration
$ppsi$	Pulse-pressure-squared integral
I_{sppa}	Spatial-peak pulse-average intensity
I_{spta}	Spatial-peak temporal-average intensity
w_6	−6 dB beamwidth
I_{sata}	Spatial-average temporal-average intensity
P	Total ultrasonic power
z_{ppsi}	Distance from external transducer aperture to the position of maximum pulse-pressure-squared integral
z_{spta}	Distance from external transducer aperture to the position of spatial-peak temporal-average intensity
prr	Pulse repetition rate
srr	Scan repetition rate

For discrete scanned modes, where the scan-frame consists of N distinct scan lines, it is possible simply to examine every Nth scan line and characterize it in the same way as for an unscanned beam, except that derivation of I_{spta} needs to account for "overlap" between scan lines and derivation of P needs to include the acoustic power for all scan lines. An additional complication arises because, since the overlap between scan lines varies with distance, the position of the maximum I_{spta} will generally not be at the same distance from the transducer as the position of maximum $ppsi$ for any single scan line. It is then assumed that, as the complexity of the field increases, it remains possible to isolate individual discrete modes of regular repeating periods.

F.3 Need for ~~change~~ an alternative approach

However, the above approach is only possible if the number of scan lines in the scan-frame remains constant until the scanner controls are adjusted. For many modern scanners, the number of scan lines is constantly changing, which makes it impossible to synchronize the measurement process with the generation of a specific ultrasonic pulse. This means that measurements of mandatory parameters can only be carried out by manufacturers with the equipment operating in dedicated engineering modes. Moreover, these measurements are extremely time-consuming to perform and their value to determining either the performance or the safety of imaging equipment is questionable.

F.4 Proposed ~~changes~~ approach

F.4.1 Alternative philosophy

The alternative approach suggested here does not require synchronization with the scan-frame. At least the parameters that are relevant to the continued safe use of ultrasound imaging should be included. At present, this means factors that may affect heating and cavitation (or other bubble activity). It needs to be possible to measure these parameters for any field without special knowledge of the scanner (although it would be expected that such knowledge will allow measurements to be carried out more rapidly). However, it should also be possible to use existing measurement methods and infrastructure and to calculate values for the field by an appropriate combination of quantities for the individual pulses.

This is an important consideration because it allows manufacturers and other laboratories to continue to use their existing measurement infrastructure.

As far as possible, the required acoustic parameters will be based on a subset of the existing parameters defined by IEC but modified to account for the change of philosophy, which means that the field no longer consists of a repeating pattern of discrete pulses each of a well-defined centre frequency.

F.4.2 Alternative parameters

For systems that do not meet the narrow-band requirements, recording of the time waveform is required and any correction required or recommended in other clauses of this document for limited **bandwidth** or finite sensor dimensions should be applied also. However, the new parameters are mostly chosen so that, for a system that does meet the narrow-band requirements, they can be determined with a system which can only measure peak pressures and RMS voltage.

NOTE In general, diagnostic and high intensity focused ultrasound (HIFU) equipment meets the narrow-band requirements at maximum output levels only via a broadband flat **hydrophone** frequency response, see 5.1.7.

The exception to this is the **acoustic-working frequency** which, as at present, will require the ability to carry out spectral analysis. Table F.2 presents a list of parameters that are to be used or are to be deleted.

Table F.2 – List of parameters that are to be used or are to be deleted

p_c	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
p_r	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
f_{awf}	Calculate from pressure spectrum measured over 1 s or more, or from Fourier analysis of the pulse containing the peak negative pressure (see below for more details). For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
t_d	Not required. The existing definition of pulse duration makes measurement of it subject to substantial **uncertainty** and error depending on the frequency response of the measurement system. Moreover, a single value for pulse duration is only relevant if all acoustic pulses are identical.
$ppsi$	Not required. Pulse-intensity integral is currently used to define the axis and focus of individual pulses and to calculate spatial-peak pulse-average intensity.
I_{sppa}	Not required. Spatial-peak pulse-average intensity is subject to large **uncertainties** due to the definition of pulse duration. Since it is unlikely to be of direct relevance to safety, this parameter can be dropped. The limit placed on I_{sppa} by the Food and Drug Administration in the USA in their FDA510(k) should be removed completely or replaced with a limit on Mechanical Index (MI) or p_r.
I_{spta}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
w_6	Calculated from I_{spta} and p_r distributions, not from $ppsi$. The diameter of an individual ultrasound beam may be of interest for some aspects of performance but is not relevant for safety. The diameter of the temporal-average intensity and peak-rarefactional acoustic pressure distributions, however, are relevant to safety. Beam areas (which are used in the definition of I_{sata}) can be defined on the same basis. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
I_{sata}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
P	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
z_{ppsi}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
z_{spta}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
prr	Not required.
srr	Not required.

F.5 Measurement methods

F.5.1 General

Measurements will be made with an appropriate **hydrophone assembly**. Observation at any point should be carried out for long enough that a fully representative part of the acoustic signal is sampled. Typically, this would be less than 1 s.

New technology oscilloscopes and digital capture cards are now available which allow extremely long recording lengths to be captured and analysed. In general, use of such a device is likely to be the most flexible way to determine all the necessary parameters. Since it is no longer assumed that the acoustic signal will repeat, equivalent-time sampling is not possible and consequently the single-shot digital **bandwidth** will need to be sufficient to accurately represent the **hydrophone** signal.

F.5.2 Peak pressures

Many acoustic pulses can be captured and a search carried out for the peak positive and negative values. Pulses above a certain threshold can be captured selectively. As a simpler alternative, a suitable "envelope" mode or peak-detect circuit can be used.

F.5.3 Temporal-average intensity

The most general method is to digitize every acoustic pulse and calculate the **temporal-average intensity** from this data. Clearly, this will be easier if an electrical trigger signal corresponding to each acoustic firing is available. In the absence of such a trigger signal, capture can be initiated by triggering on the waveform or simply by initiating a continuous acquisition sequence. In these latter two cases, it may be necessary to pre-process the waveform data to minimize electrical noise and to remove non-acoustic signals.

NOTE In many cases, a very high sample rate ~~may~~ is not expected to be required to measure I_{spta} since the energy in the N^{th} nonlinear harmonic is less than or equal to $1/N^2$ times the energy in the fundamental.

In principle, I_{ta} can be measured more simply with an RMS voltmeter (or radio frequency power meter) fitted with an appropriate voltage sensor. In practice, electrical noise and the temporal response of the sensor may cause some difficulties at lower levels of I_{ta}. However, for most clinical fields where I_{spta} approaches the current FDA510(k) limits of 720 mW cm^{-2} (derated), it is possible to use this method to locate and measure the peak value and to measure the −6 dB **beamwidth**.

F.5.4 Frequency

From the perspective of a safety standard, we can consider two different reasons for wanting to know the **acoustic frequency**. The first relates to the occurrence of cavitation and its relevant quantity is approximately the centre frequency of the pulse with the largest negative pressure. The second reason relates to heating and the relevant quantity is approximately the median of the acoustic pressure spectrum. In single mode operation, these two quantities are likely to be similar. However, for combined modes, these two quantities may be significantly different. For instance, in B+CF imaging, the scan-frame generally consists of a small number of short, high amplitude pulses for grey-scale imaging and a larger number of longer, lower amplitude Doppler pulses. The centre frequency of each type of pulse may lie anywhere within the **bandwidth** of the transducer.

Consequently, two distinct frequency parameters are suggested for each of these two requirements.

- Mechanical acoustic frequency is determined at the point where the negative pressure reaches its global maximum value. This frequency is defined as **peak pulse acoustic frequency** f_p.
- Thermal acoustic frequency~~, f_t:~~ is determined at the position where the temporal-average intensity reaches its global maximum value. This frequency is defined as~~: **time**~~ temporal-average acoustic frequency f_t.

NOTE 1 It ~~may~~ can be necessary to correct for frequency-dependent sensitivity of the **hydrophone** and amplifier in order to correctly determine the time averaged acoustic pressure spectrum, especially in cases where there are two or more widely separated spectral peaks of similar magnitude.

NOTE 2 The detailed procedure to obtain the appropriate acoustic power spectrum has not yet been elaborated.

F.5.5 Power

Power should be measured with a radiation force balance or by planar scanning with an appropriate **hydrophone**.

F.6 Discussion

F.6.1 Relationship to existing standards

F.6.1.1 IEC 61157

A change would be that, while measurements would still be made at the position of the maximum **peak-rarefactional acoustic pressure** p_r, the other location would now be at the position of the maximum spatial-peak temporal average intensity, I_{spta}, rather than at the maximum of the pulse-pressure-squared-integral for a single pulse type.

The exemption clause for low output equipment would remain and would be based on the same parameters as currently specified, except that the definition of **output beam area** would need to be altered to refer to I_{spta}. This may affect the value of I_{ob} for some scanned systems, but not for the unscanned systems that generally fall into the exempt group.

F.6.1.2 IEC 62359 and IEC 60601-2-37

In principle, these would not be greatly changed. The major difference would be in the calculation of those Thermal Index (*TI*) formulae that depend on the variation of intensity with distance along the axis. Currently, the *TI* for each type of pulse is calculated independently and combined in a not altogether satisfactory way to arrive at a value for the scan pattern. With the new approach, the temporal-average intensity for the entire scan-pattern is measured (or calculated) and the axial variation of this quantity determines the distance and the value of the *TI*. This change would also be carried through to calculating the equivalent beam diameter as a function of distance. A further minor change would be in the value used for the **acoustic-working frequency**, which affects the derating calculation and is also used explicitly in the soft tissue *TI* calculations. The alternative approach is actually a more consistent implementation of the *TI* concept and, for unscanned fields, the results should be identical.

For the Mechanical Index (*MI*), the value of the frequency used in the formula may be different in some cases.

F.6.2 Advantages

The major benefits appear to be substantial.

- The number of measurements required and the number of declared parameters are greatly reduced since only two sets of measurements are now required for each probe, instead of two sets for each operational mode of each **ultrasonic transducer**.
- The definitions of the new parameters can be applied to even more complicated output patterns and sequences in the future as new imaging techniques are developed.
- Measurements on even complex **operating modes** can be made with relatively straightforward measuring equipment.

Existing measurement methods can still be used and should generate consistent results. For simple, unscanned systems (and perhaps for many others), the values of the acoustic quantities will be unchanged from the existing definitions.

F.6.3 Disadvantages

The technical disadvantages include:

- the introduction of a second frequency quantity;
- possible susceptibility of the method ~~may be susceptible~~ to electrical noise;
- possible need to make minor changes ~~might be required~~ to existing measurement techniques and equipment;
- a requirement of significant wave memory for a long-term (> 1 s) sequence.

Annex G
(informative)

Propagation medium and degassing

It is well established that measurements can be strongly affected by acoustic cavitation. Cavitation is the growth, oscillation and collapse of previously existing gas- or vapour-filled microbubbles in a medium. During ultrasonic measurements, these bubbles will scatter the ultrasound from the transducer under test, causing instabilities and underestimates of the values to be measured. There is thus a need to know when cavitation is occurring during measurements, and also to define suitable media in which the effects of cavitation can be minimized.

A measurement method to detect the onset of cavitation is described in [93], [94]. Specifically, the onset of inertial cavitation is often characterized by the presence of the subharmonic of the fundamental operating frequency. An example of an acoustic spectrum acquired using a needle **hydrophone** is presented in [93], [94].

Possible methods to degas the water are investigated in [95] and listed in IEC/~~TS~~ TR 62781.

Annex H
(informative)

Specific ultrasonic fields

H.1 Diagnostic fields

H.1.1 Useful relationships between acoustical parameters

A number of useful relationships exist between various acoustical parameters, which can be used to check consistency of acoustic output measurements. Some of these are given below.

The **spatial-peak pulse-average intensity**, I_{sppa}, is related to the **spatial-peak temporal-average intensity**, I_{spta}, by

$$I_{sppa} = prp \times I_{spta} / t_d \quad \text{(H.1)}$$

To determine the total **ultrasonic power**, the procedures and techniques described in 7.3.2.4 or IEC 61161 may be used. If the total **ultrasonic power**, P, is known, then it is possible to determine values for the **spatial-average temporal-average intensity**, which are over-estimates. If P_{beam} refers to the total power emitted by one acoustic scan line for an automatic scanner then the following equalities and inequalities hold:

~~P = Total number of acoustic scan lines x P_{beam}~~

~~For non-automatic scanning systems:~~

~~P/A_b > spatial-average temporal-average intensity~~

~~For automatic scanning systems:~~

~~*P*/(*scan area*) > spatial-average temporal-average intensity~~

~~*scan width* > s_s x total number of acoustic scan lines~~

~~where s_s is the **ultrasonic scan line separation** (see 3.72).~~

$$P = n_{sl} \times P_{beam} \quad \text{(H.2)}$$

where

n_{sl} is the total number of acoustic scan lines.

NOTE Formula (H.2) assumes the same **number of pulses per ultrasonic scan line** n_{pps} for each scan line.

For **non-scanning modes**:

$$P/A_b > I_{sata}$$

For **scanning modes**:

$$P/A_{scan} > I_{sata}$$

and:

$$w_{scan} > s_s \times n_{ts}$$

where

I_{sata} is the **spatial-average temporal-average intensity**;

A_{scan} is the scan area;

w_{scan} is the scan width;

s_s is the **ultrasonic scan line separation** (see 3.87).

It is assumed here that the scan lines are equally spaced, which is not necessarily the case. For some types of transducer, such as a linear array, "scan width" represents the width of the scan in a straight line parallel to the linear array surface and is independent of the distance from the face (rectilinear scan geometry). For other transducers, such as sector scanners, "scan width" represents the width of the scan on a surface centred at a point, usually within the transducer body. In this case, the "scan width" depends on the distance specified for s_s.

H.1.2 Pulsed wave diagnostic equipment

In all pulsed wave diagnostic equipment, a pulsed waveform is transmitted and either the echo or the transferred signal is analysed.

The acoustic output of pulse-echo diagnostic equipment usually consists of ~~a single pulse~~ pulses of ultrasound at an **acoustic-working frequency** in the range 1 MHz to ~~12~~ 20 MHz, and at **pulse repetition rates** of between 1 kHz and ~~5~~ 25 kHz. Pulsed Doppler equipment usually has an acoustic pulse consisting of a number of cycles at **pulse repetition rates** similar to or perhaps higher than pulse-echo equipment. In both types of equipment, the ultrasound is usually focused at distances from the transducer of between a few centimetres and 20 cm, and the **peak acoustic pressure** at the focus is usually between 0,2 MPa and 10 MPa. While linear-array, sector and phased-array scanners emit consecutive pulses along different **ultrasonic scan lines**, the **acoustic pulse waveform** remains approximately constant.

For pulse-echo equipment, the focal diameter is usually less than about 3 mm and, as seen from 5.1.6, a **hydrophone** with an active element of diameter approximately 0,5 mm is needed as well as a relatively precise alignment of the **hydrophone**.

NOTE Some pulse-echo equipment uses unfocused beams in some applications and achieves spatial resolution within the receiving procedures.

As the acoustic pressures are high, the **local distortion parameter** σ_q (see 3.38) will usually be greater than 0,5, in which case the **bandwidth** requirement for the **hydrophone** is greater and additional demands are placed on the angular alignment because of the dependence of this directional response on frequency. Under these conditions, it is important to optimize the rotation of the **hydrophone** to ensure the maximum received signal (see 5.2.2).

In general, diagnostic equipment places the greatest demand on the **hydrophone bandwidth** and on the coordinate positioning system. PVDF **hydrophones** of the membrane or needle type are essential (see Clause B.9). Several investigations have shown the need for broadband **hydrophones** [25], [36], [96], [97].

As measurements for the purpose of determining the maximum output are undertaken in the plane containing the **spatial-peak temporal-peak acoustic pressure**, this plane is expected to be close to the focus of the transducer. At typical focal distances, the square law relationship between acoustic pressure and intensity is usually assumed in order to derive intensity parameters. This assumption is made despite the **uncertainty** associated with the nonlinear distortion that can take place.

H.1.3 Continuous wave diagnostic equipment

Frequencies for continuous wave Doppler systems are usually between 2 MHz and 10 MHz, and an acoustic lens can be used to focus the ultrasound at distances from the transducer face of up to 8 cm. Sometimes the transducer elements have D-shaped crystals, which makes identifying the maxima in any plane complex. **Peak acoustic pressures** are usually less than 0,1 MPa and, consequently, the **local distortion parameter** is generally below 0,5 and a broadband **hydrophone** does not need to be used.

Focal diameters may be less than 3 mm and, as seen from 5.1.6, a **hydrophone** with an active element of diameter 0,5 mm or smaller is needed. For higher frequency devices, it may be necessary to rotate the **hydrophone** when measurements are made at distances from the acoustic axis greater than the transducer radius.

In the case of foetal monitors, the acoustic beam is often divergent, and the **peak acoustic pressure** usually occurs at the face of the **ultrasonic transducer**. Under these circumstances, the usual plane progressive wave approximation for ultrasonic intensity is invalid (see 7.3). Hence, only acoustic pressure parameters can be specified unless a compromise is made. Such a compromise is to undertake measurements in a plane that does not contain the **spatial-peak temporal-peak acoustic pressure** in the whole acoustic field and at a distance such that the plane progressive wave approximation for intensity may be assumed. Although not strictly appropriate for a divergent beam, the criterion given in reference [70] for a plane piston transducer may be used to estimate the difference between the true intensity and the intensity derived from the square of the acoustic pressure. A suitable compromise is to undertake measurements at a distance from the face of the **ultrasonic transducer** of between one and two **ultrasonic transducer element** diameters. For a plane piston transducer, this would yield errors of 4 % and < 2 % for these two cases.

H.2 Therapy fields

H.2.1 Physiotherapy equipment

Ultrasonic transducers used for physiotherapy usually operate between 0,75 MHz and 3 MHz under continuous wave or long tone-burst excitation. IEC 61689 is the related measurement standard. For systems in the frequency range from 20 kHz to 500 kHz, IEC 63009 is the related measurement standard.

Typically, the transducers have active elements of diameter 20 mm and may have an acoustic lens to modify the ultrasonic field. **Peak acoustic pressures** are below 0,5 MPa with no significant nonlinear distortion of the acoustic pressure waveform taking place in the **near field** of the transducer.

General measurements can be made in any plane although it is usual to require them to be made in the **near field**. For measurements made at distances of less than two transducer diameters, there is the same problem of conversion from acoustic pressure to intensity as with the continuous wave Doppler devices (see H.1.3). So, to obtain an absolute value of intensity, it is recommended that measurements are made at distances from the transducer which are greater than or equal to one transducer diameter.

~~H.2.2 Hyperthermia~~

~~This clause is reserved for specific comments for High Intensity Focussed Ultrasound (HIFU) equipment, they are under development.~~

H.2.2 High intensity therapeutic ultrasonic equipment

Specific comments on the measurement of fields generated by high intensity focused ultrasound (HIFU) and high intensity therapeutic ultrasound (HITU) are specified in IEC TS 62556 with respect to measurement at relatively low output levels and methodology for extrapolating these to higher therapeutic level fields.

H.2.3 Non-focused and weakly focused pressure pulses

Specific comments on the measurement of fields generated by non-focusing pressure pulse sources for pain treatment and other applications are specified in IEC 63045.

H.3 Surgical fields

H.3.1 Lithotripters

Specific comments on the measurement of fields generated by pressure pulse lithotripters are specified in IEC 61846.

H.3.2 Low frequency surgical applications

Specific comments on the measurement of fields generated by low frequency surgical systems are specified in IEC 61847.

Annex I
(informative)

Assessment of uncertainty in the acoustic quantities obtained by hydrophone measurements

I.1 General

To be truly meaningful, the result of a measurement should be accompanied by its associated **uncertainty**. 6.4.2 states that, in evaluating and expressing the **uncertainty** in the calibration, the guidance provided by ISO/IEC Guide 98-3:2008 shall be followed.

In general, **uncertainty** components are grouped according to how the values are estimated:

Type A: evaluated by statistical means;

Type B: evaluated by other means.

I.2 Overall (expanded) uncertainty

The overall **uncertainty** should be obtained from all **uncertainty** components in the manner described in ISO/IEC Guide 98-3:2008.

When combining **uncertainty** components, care should be taken when component values are expressed in decibels. Before combination, the values should be expressed in linear form (e.g. as a percentage or in the units of the quantity) and not in ~~decibels~~ logarithmic form. The final value of expanded **uncertainty** may be expressed either in the units of the quantity, as a percentage or converted to decibels as required.

NOTE 1 ~~It should be realized that~~ The use of decibels to express **uncertainties** ~~may~~ can lead to asymmetric distributions (e.g. +1,5 dB is equivalent to +19 %, but −1,5 dB is equivalent to −16 %).

NOTE 2 When each component of **uncertainty** is small, i.e. less than 1 dB, the overall **uncertainty** can be calculated using decibels.

I.3 Common sources of uncertainty

The following is a list of common sources of **uncertainty** using **hydrophones**. This list should not be considered exhaustive but may be used as a guide when assessing **uncertainties** for a specific parameter. Depending on the parameter to be measured, some (though possibly not all) of these sources will need assessment. For example, the errors from measuring instruments might be minimized by the use of the same measuring channel (amplifier, filter, voltmeter, etc.) for all signals and measuring only amplitude ratios. However, since this might not be the case in all implementations, components for these sources of error have been included in the list.

Various potential sources of **uncertainty** are as given below.

a) Due to alignment and waterbath:
   1) positioning of the **hydrophone** for maximum signal;
   2) misalignment, particularly at high frequencies where the **hydrophone** response may be far from omnidirectional;
   3) interference from acoustic reflections, leading to a lack of free-field conditions;
   4) acoustic scattering from the **hydrophone** mount (or vibrations picked up and conducted by the mount);
   5) bubbles or air clinging to transducer and or **hydrophone** – this should be minimized by adequate wetting and soaking of transducers and **hydrophones**;

6) cavitation bubbles and dust particles in the water;
7) variation in environmental conditions during the measurements (e.g. temperature, depth, mounting/rigging, etc.);
8) errors in the measurement of distances.

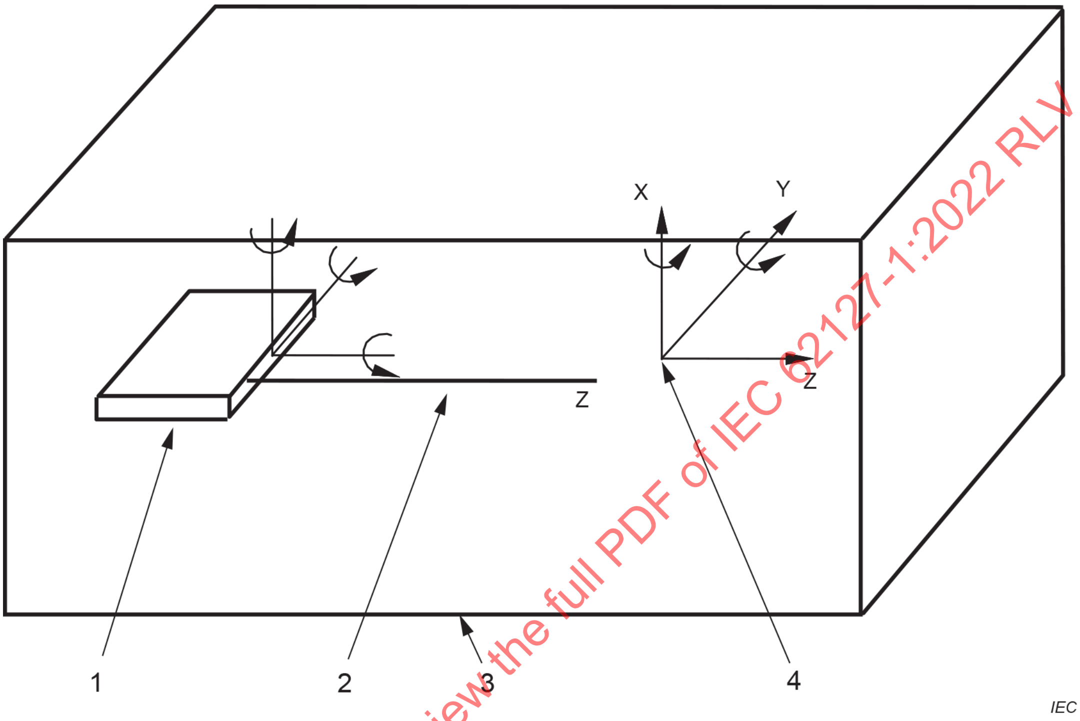
b) Errors related to signal management:
1) **hydrophone** sensitivity data;
2) electrical noise on the **hydrophone** signal include RF pick-up;
3) additional noise through waveform deconvolution (see 5.1.7.2);
4) error due to regularization filtering for deconvolution (see 5.1.7.2.3);
5) inaccuracy of any electrical loading corrections made to account for loading by extension cables and preamplifiers;
6) inaccuracy of any electrical signal attenuators used;
7) errors due to the lack of linearity in the measurement system (the use of a calibrated attenuator to equalize the measured signals may significantly reduce this contribution);
8) inaccuracy of the gains of any amplifiers, filters and digitizers used;
9) errors in measurement of the receive voltage (including the accuracy of the measuring instrumentation – voltmeter, digitizers, etc.);
10) errors due to the resolution of the digitizer;
11) errors in the time base.

c) Errors related to the ultrasonic field:
1) overlapping acoustic scan lines;
2) variation between scan lines;
3) lack of steady-state conditions;
4) errors in the values for acoustic frequency;
5) errors in the values for water density;
6) local temperature variations between repeated measurements;
7) instability of ultrasound transducer (e.g. instability of the output or electrical drive conditions);
• ~~hydrophone calibration;~~
8) instability of the **hydrophone**;
9) temperature sensitivity of the **hydrophone**;
10) nonlinear distortion;
11) the spatial averaging effects of the **hydrophones** due to their finite size.

Annex J
(informative)

Transducer and hydrophone positioning systems

There are numerous ways to mount the **ultrasonic transducer** and **hydrophone** such that the requirements specified in 5.2 ~~may~~ can be met. Figure J.1 illustrates a possible system.



Key

1 **ultrasonic transducer** (linear array)(translations optional)

2 beam axis

3 tank

4 hydrophone active element

X, Y and Z denote the axis directions relative to the mounted **hydrophone** and **ultrasonic transducer**

Figure J.1 – Schematic diagram of the ultrasonic transducer and hydrophone degrees of freedom

Annex K
(informative)

Beamwidth midpoint method

In the method[5], orthogonal line scans are used and the square root of **pulse-pressure-squared-integral** values, $ppsi$, are divided into 20 intervals corresponding to the −0,1 dB to −26 dB level. See Table K.1.

Beamwidths are calculated at as many of the table decibel levels as signal level will permit, and the locations of their centres are averaged together to obtain **beamwidth midpoints** for both x and y. The intersection of lines perpendicular to scan lines and passing through the midpoints is the **beam centrepoint.**

~~In Table K.1 below, "*ppsi*" refers to **pulse-pressure-squared-integral.**~~

Table K.1 – Decibel beamwidth levels for determining midpoints

Normalized ~~SQRT(*ppsi*)~~ $\sqrt{ppsi}$ Linear	Normalized $ppsi$ Linear	Levels dB
0,988 5	0,977 1	−0,100 6
0,95	0,902 5	−0,445 5
0,9	0,810 0	−0,915 1
0,85	0,722 5	−1,411 6
0,8	0,640 0	−1,938 2
0,75	0,562 5	−2,498 8
0,7	0,490 0	−3,098 0
0,65	0,422 5	−3,741 7
0,6	0,360 0	−4,437 0
0,55	0,302 5	−5,192 7
0,5	0,250 0	−6,020 6
0,45	0,202 5	−6,935 7
0,4	0,160 0	−7,958 8
0,35	0,122 5	−9,118 6
0,3	0,090 0	−10,457 6
0,25	0,062 5	−12,041 2
0,2	0,040 0	−13,979 4
0,15	0,022 5	−16,478 2
0,1	0,010 0	−20,000 0
0,05	0,002 5	−26,020 6

5 The beamwidth midpoint method is adapted from an approach developed by TNO, Prevention and Health, Leiden, the Netherlands.

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IEC 60601-2-37, *Medical electrical equipment – Part 2-37: Particular requirements for the basic safety and essential performance of ultrasonic medical diagnostic and monitoring equipment*

IEC 60601-2-62, *Medical electrical equipment – Part 2-62: Particular requirements for the basic safety and essential performance of high intensity therapeutic ultrasound (HITU) equipment*

IEC TR 60854, *Methods of measuring the performance of ultrasonic pulse-echo diagnostic equipment*

IEC 61157, *Standard means for the reporting of the acoustic output of medical diagnostic ultrasonic equipment*

IEC 61161, *Ultrasonics – Power measurement – Radiation force balances and performance requirements*

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IEC 62127-1

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Ultrasonics – Hydrophones –
Part 1: Measurement and characterization of medical ultrasonic fields

Ultrasons – Hydrophones –
Partie 1: Mesurage et caractérisation des champs ultrasoniques médicaux

IEC 62127-1:2022-03(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ULTRASONICS – HYDROPHONES –

Part 1: Measurement and characterization of medical ultrasonic fields

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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IEC 62127-1 has been prepared by IEC technical committee 87: Ultrasonics. It is an International Standard.

This second edition cancels and replaces the first edition published in 2007 and Amendment 1:2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition.

a) The upper frequency limit of 40 MHz has been removed.
b) Hydrophone sensitivity definitions have been changed to recognize sensitivities as complex-valued quantities.
c) Procedures and requirements for narrow-band approximation and broadband measurements have been modified; details on waveform deconvolution have been added.
d) Procedures for spatial averaging correction have been amended.
e) Annex D, Annex E and bibliography have been updated to support the changes of the normative parts.

The text of this International Standard is based on the following documents:

Draft	Report on voting
87/783/FDIS	87/788/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of IEC 62127 series, published under the general title *Ultrasonics – Hydrophones*, can be found on the IEC website.

NOTE Words in **bold** in the text are terms defined in Clause 3.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

The main purpose of this document is to define various acoustic parameters that can be used to specify and characterize ultrasonic fields propagating in liquids, and, in particular, water, using hydrophones. Measurement procedures are outlined that may be used to determine these parameters. Specific device related measurement standards, for example IEC 61689, IEC 61157, IEC 61847 or IEC 62359, can refer to this document for appropriate acoustic parameters. In IEC 62359, some additional measurement methods for attenuated parameters and indices are described addressing the specific needs of acoustic output characterization of ultrasonic diagnostic equipment in accordance with IEC 60601-2-37.

The philosophy behind this document is the specification of the acoustic field in terms of acoustic pressure parameters, acoustic pressure being the primary measurement quantity when hydrophones are used to characterize the field.

Intensity parameters are specified in this document, but these are regarded as derived quantities that are meaningful only under certain assumptions related to the ultrasonic field being measured.

ULTRASONICS – HYDROPHONES –

Part 1: Measurement and characterization of medical ultrasonic fields

1 Scope

This part of IEC 62127 specifies methods of use of calibrated **hydrophones** for the measurement in liquids of acoustic fields generated by ultrasonic medical equipment including **bandwidth** criteria and calibration frequency range requirements in dependence on the spectral content of the fields to be characterized.

This document:

- defines a group of acoustic parameters that can be measured on a physically sound basis;
- defines a second group of parameters that can be derived under certain assumptions from these measurements, and called derived intensity parameters;
- defines a measurement procedure that can be used for the determination of acoustic pressure parameters;
- defines the conditions under which the measurements of acoustic parameters can be made using calibrated **hydrophones**;
- defines procedures for correcting for limitations caused by the use of **hydrophones** with finite **bandwidth** and finite active element size, and for estimating the corresponding **uncertainties**.

NOTE 1 Throughout this document, SI units are used. In the specification of certain parameters, such as **beam areas** and intensities, it can be convenient to use decimal multiples or submultiples. For example, **beam area** is likely to be specified in cm^2 and intensities in W/cm^2 or mW/cm^2.

NOTE 2 The **hydrophone** as defined can be of a piezoelectric or an optic type.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60565-1, *Underwater acoustics – Hydrophones – Calibration of hydrophones – Part 1: Procedures for free-field calibration of hydrophones*

IEC 61689, *Ultrasonics – Physiotherapy systems – Field specifications and methods of measurement in the frequency range 0,5 MHz to 5 MHz*

IEC 62127-2, *Ultrasonics – Hydrophones – Part 2: Calibration for ultrasonic fields up to 40 MHz*

IEC 62127-3, *Ultrasonics – Hydrophones – Part 3: Properties of hydrophones for ultrasonic fields up to 40 MHz*

IEC 63009, *Ultrasonics – Physiotherapy systems – Field specifications and methods of measurement in the frequency range 20 kHz to 500 kHz*

ISO 16269-6, *Statistical interpretation of data – Part 6: Determination of statistical tolerance intervals*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62127-2, IEC 62127-3 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
acoustic pulse waveform
temporal waveform of the **instantaneous acoustic pressure** at a specified position in an acoustic field and displayed over a period sufficiently long to include all significant acoustic information in a single pulse or tone-burst, or one or more cycles in a continuous wave

Note 1 to entry: Temporal waveform is a representation (e.g. oscilloscope presentation or equation) of the **instantaneous acoustic pressure**.

3.2
acoustic repetition period
arp
pulse repetition period for non-automatic scanning systems and the **scan repetition period** for automatic scanning systems, equal to the time interval between corresponding points of consecutive cycles for continuous wave systems

Note 1 to entry: The **acoustic repetition period** is expressed in seconds (s).

3.3
acoustic-working frequency
acoustic frequency
frequency of an acoustic signal based on the observation of the output of a **hydrophone** placed in an acoustic field at the position corresponding to the **spatial-peak temporal-peak acoustic pressure**

Note 1 to entry: The signal is analysed using either the **zero-crossing acoustic-working frequency** technique or a spectrum analysis method. Acoustic-working frequencies are defined in 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.5.

Note 2 to entry: In a number of cases the present definition is not very helpful or convenient, especially for **broadband transducers**. In that case, a full description of the frequency spectrum is expected to be given in order to enable any frequency-dependent correction to the signal.

Note 3 to entry: **Acoustic frequency** is expressed in hertz (Hz).

3.3.1
zero-crossing acoustic-working frequency
f_{awf}
number, n, of consecutive half-cycles (irrespective of polarity) divided by twice the time between the commencement of the first half-cycle and the end of the n-th half-cycle

Note 1 to entry: None of the n consecutive half-cycles are expected to show evidence of phase change.

Note 2 to entry: The measurement are performed at terminals in the receiver that are as close as possible to the receiving transducer (**hydrophone**) and, in all cases, before rectification.

Note 3 to entry: This frequency is determined according to the procedure specified in IEC TR 60854.

Note 4 to entry: This frequency is intended for continuous-wave systems only.

3.3.2
arithmetic-mean acoustic-working frequency
f_{awf}
arithmetic mean of the most widely separated frequencies f_1 and f_2, within the range of three times f_1, at which the level of the acoustic pressure spectrum is 3 dB below the peak level

Note 1 to entry: This frequency is intended for pulse-wave systems only.

Note 2 to entry: It is assumed that $f_1 < f_2$.

Note 3 to entry: If f_2 is not found within the range < $3f_1$, f_2 is to be understood as the lowest frequency above this range at which the spectrum level is 3 dB below the peak level.

3.3.3
magnitude-weighted acoustic-working frequency
f_{awf}
frequency weighted with the spectral acoustic pressure magnitude in the frequency range where the spectral pressure level is equal to or larger than 3 dB below the peak level

$$f_{awf} = \frac{\int f \left|\underline{P}(f)\right| \mathrm{d}f}{\int \left|\underline{P}(f)\right| \mathrm{d}f} \quad \text{with} \quad \left|\underline{P}(f)\right| = \begin{cases} \left|\underline{P}(f)\right| & \text{if } L_P(f) \geq \max L_P(f) - 3\,\mathrm{dB} \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

where

f is the frequency of the acoustic pressure spectrum;

$|\underline{P}(f)|$ is the modulus of the complex-valued spectrum of the **acoustic pulse waveform**;

$L_P(f)$ is the pressure level spectrum given from $L_P(f) = 20\log_{10}\left(\frac{\left|\underline{P}(f)\right|}{P_{ref}}\right)\mathrm{dB}$ with P_{ref} = 1 Pa.

Note 1 to entry: This frequency is intended for pulse-wave systems only.

Note 2 to entry: The integrals in Formula (1) are definite, to be taken from the minimum to the maximum of the acquired signal spectrum.

Note 3 to entry: The restriction to the range with pressure levels equal to or larger than −3 dB of the peak level is required to avoid the influence of higher harmonic frequencies on the **acoustic-working frequency**.

Note 4 to entry: Definition 3.3.3 leads to more stable **acoustic-working frequency** results than definition 3.3.2 if there are peaks in the acoustic pressure spectrum close to the −3 dB threshold. This is particularly relevant for the determination of derated field parameters as required in IEC 62359 using a single derating factor depending on the **acoustic-working frequency**.

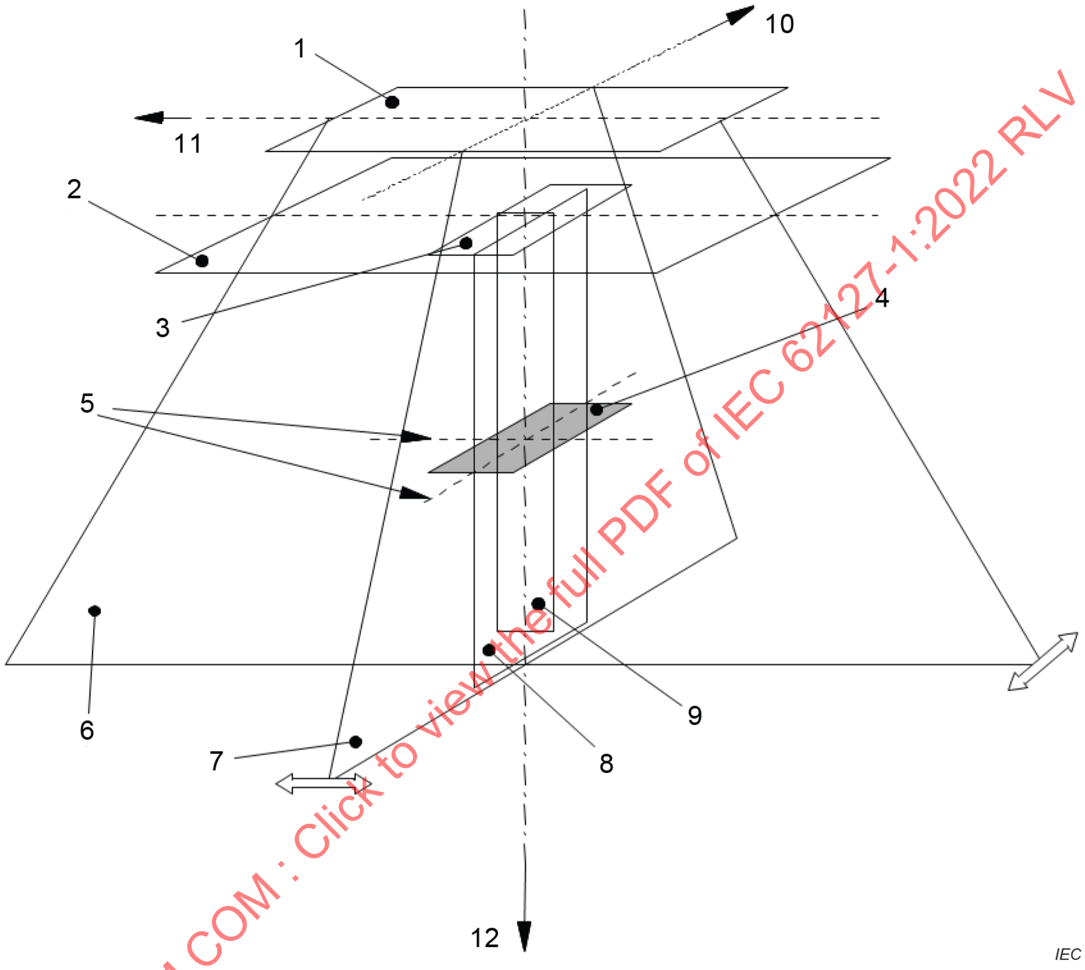
3.3.4
peak pulse acoustic frequency
f_p
acoustic-working frequency of the pulse with the largest **peak negative acoustic pressure** measured at the point of maximum **peak negative acoustic pressure**

3.3.5
temporal-average acoustic frequency
f_t
acoustic-working frequency of the time averaged acoustic pressure spectrum of the acoustic signals measured at the point of maximum **temporal-average intensity**

3.4
azimuth axis
axis formed by the junction of the **azimuth plane** and the **source aperture plane** (measurement) or **transducer aperture plane** (design)

SEE: Figure 1

[SOURCE: IEC 61828:2020, 3.7]



Key

1	external transducer surface plane	7	azimuth plane, scan plane
2	source aperture plane	8	principal longitudinal plane
3	source aperture	9	longitudinal plane
4	beam area plane	10	X, azimuth axis
5	beamwidth lines	11	Y, elevation axis
6	elevation plane	12	Z, beam axis

[SOURCE: IEC 61828:2020]

Figure 1 – Schematic diagram of the different planes and lines in an ultrasonic field

3.5
azimuth plane
plane containing the **beam axis** and the line of the minimum **full width half maximum beamwidth**

SEE: Figure 1

Note 1 to entry: For an **ultrasonic transducer** array, this is the imaging plane.

Note 2 to entry: For a single **ultrasonic transducer** with spherical or circular symmetry, it is any plane containing the **beam axis**.

[SOURCE: IEC 61828:2020, 3.8]

3.6
bandwidth
BW
difference in the most widely separated frequencies f_1 and f_2 at which the level of the acoustic pressure spectrum becomes 3 dB below the peak level, at a specified point in the acoustic field

Note 1 to entry: **Bandwidth** is expressed in hertz (Hz).

3.7
beam area
$A_{b,6}$, $A_{b,20}$
area in a specified plane perpendicular to the **beam axis** consisting of all points at which the **pulse-pressure-squared integral** is greater than a specified fraction of the maximum value of the **pulse-pressure-squared integral** in that plane

Note 1 to entry: If the position of the plane is not specified, it is the plane passing through the point corresponding to the maximum value of the **pulse-pressure-squared integral** in the whole acoustic field.

Note 2 to entry: In a number of cases, the term **pulse-pressure-squared integral** is replaced everywhere in the above definition by any linearly related quantity, for example

a) in the case of a continuous wave signal the term **pulse-pressure-squared integral** is replaced by mean square acoustic pressure as defined in IEC 61689,

b) in cases where signal synchronization with the scanframe is not available the term **pulse-pressure-squared integral** may be replaced by **temporal average intensity.**

Note 3 to entry: Some specified fractions are 0,25 and 0,01 for the −6 dB and −20 dB beam areas, respectively.

Note 4 to entry: **Beam area** is expressed in units of metre squared (m^2).

3.8
beam axis
straight line that passes through the **beam centrepoints** of two planes perpendicular to the line which connects the point of maximal **pulse-pressure-squared integral** with the centre of the **external transducer aperture**

SEE: Figure 1

Note 1 to entry: The location of the first plane is the location of the plane containing the maximum **pulse-pressure-squared integral** or, alternatively, is one containing a single main lobe which is in the focal Fraunhofer zone. The location of the second plane is as far as is practicable from the first plane and parallel to the first with the same two orthogonal scan lines (x and y axes) used for the first plane.

Note 2 to entry: In a number of cases, the term **pulse-pressure-squared integral** is replaced in the above definition by any linearly related quantity, for example

a) in the case of a continuous wave signal the term **pulse-pressure-squared integral** is replaced by mean square acoustic pressure as defined in IEC 61689,

b) in cases where signal synchronization with the scanframe is not available the term **pulse-pressure-squared integral** may be replaced by **temporal average intensity**.

3.9
beam centrepoint
position determined by the intersection of two lines in the same beam area plane xy passing through the **beamwidth midpoints** of two orthogonal planes, xz and yz, perpendicular to their respective beamwidth lines

[SOURCE: IEC 61828:2020, 3.15, modified – In the definition, "in the same beam area plane xy" and ", perpendicular to their respective beamwidth lines" have been added.]

3.10
beamwidth midpoint
linear average of the location of the centres of **beamwidth**s in a plane

Note 1 to entry: The **beamwidth** midpoint method is described in Annex K.

Note 2 to entry: The average is taken over as many **beamwidth** levels given in Table K.1 as signal level permits.

[SOURCE: IEC 61828:2020, 3.22, modified – Note 1 to entry has been replaced by new Notes to entry.]

3.11
beamwidth
w_6, w_{12}, w_{20}
greatest distance between two points on a specified axis perpendicular to the **beam axis** where the **pulse-pressure-squared integral** falls below its maximum on the specified axis by a specified amount

Note 1 to entry: In a number of cases, the term **pulse-pressure-squared integral** is replaced in the above definition by any linearly related quantity, for example

a) in the case of a continuous wave signal the term **pulse-pressure-squared integral** is replaced by mean square acoustic pressure as defined in IEC 61689,

b) in cases where signal synchronization with the scanframe is not available the term **pulse-pressure-squared integral** can be replaced by **temporal average intensity**.

Note 2 to entry: Commonly used **beamwidths** are specified at −6 dB, −12 dB and −20 dB levels below the maximum. The decibel calculation implies taking 10 times the logarithm of the ratios of the integrals.

Note 3 to entry: **Beamwidth** is expressed in metres (m).

3.12
broadband transducer
transducer that generates an acoustic pulse of which the **bandwidth** is greater than the **acoustic-working frequency**

3.13
central scan line
<for automatic scanning systems> **ultrasonic scan line** closest to the symmetry axis of the **scan plane**

3.14
derived instantaneous intensity
quotient of squared **instantaneous acoustic pressure** and characteristic acoustic impedance of the medium at a particular instant in time at a particular point in an acoustic field

$$I(t) = \frac{p(t)^2}{\rho c} \qquad (2)$$

where

$p(t)$ is the **instantaneous acoustic pressure**;

ρ is the density of the medium;

c is the speed of sound in the medium

Note 1 to entry: For measurement purposes referred to in this document, the **derived instantaneous intensity** is an approximation of the **instantaneous intensity**.

Note 2 to entry: Increased **uncertainty** is expected to be taken into account for measurements very close to the transducer.

Note 3 to entry: **Derived instantaneous intensity** is expressed in units of watt per metre squared (W/m^2).

3.15
diametrical beam scan
set of measurements of the **hydrophone** output voltage made while moving the **hydrophone** in a straight line passing through a point on the **beam axis** and in a direction normal to the **beam axis**

Note 1 to entry: The **diametrical beam scan** can extend to different distances on either side of the **beam axis**.

3.16
distance z_r
z_r
distance along the **beam axis** between the plane containing the **peak-rarefactional acoustic pressure** and the **external transducer aperture**

Note 1 to entry: The **distance** z_r is expressed in metres (m).

3.17
distance z_c
z_c
distance along the **beam axis** between the plane containing the **peak-compressional acoustic pressure** and the **external transducer aperture**

Note 1 to entry: The **distance** z_c is expressed in metres (m).

3.18
distance z_{ppsi}
z_{ppsi}
distance along the **beam axis** between the plane containing the maximum **pulse-pressure-squared integral** and the **external transducer aperture**

Note 1 to entry: The **distance** z_{ppsi} is expressed in metres (m).

3.19
distance z_{spta}
z_{spta}
distance along the **beam axis** between the plane containing the **spatial-peak temporal-average intensity** and the **external transducer aperture**

Note 1 to entry: In practice, this distance is equal to the distance z_{ppsi}.

Note 2 to entry: The **distance** z_{spta} is expressed in metres (m).

3.20
effective hydrophone size
a_h
size of a theoretical receiver **hydrophone** that has a predicted **directional response** function with an angular width equal to the observed angular width

Note 1 to entry: The size is usually a function of frequency. For representative experimental data, see [1]

Note 2 to entry: The **effective hydrophone size** is expressed in metres (m).

Note 3 to entry: For hydrophones with a circular geometry, the **effective hydrophone size** is a radius.

Note 4 to entry: For hydrophones with a rectangular geometry, the **effective hydrophone size** is the half of the largest value of the length or width.

[SOURCE: IEC 62127-3:2007, 3.2, modified – In the term, "radius" has been replaced with "size". In the definition, "radius of a stiff disc receiver" has been replaced with "size of a theoretical receiver". The NOTES have been replaced.]

3.21
effective radius of a non-focusing ultrasonic transducer
a_t
radius of a perfect disc piston-like **ultrasonic transducer** that has a predicted axial acoustic pressure distribution approximately equivalent to the observed axial acoustic pressure distribution over an axial distance until at least the last axial maximum has passed

Note 1 to entry: The **effective radius of a non-focusing ultrasonic transducer** is expressed in metres (m).

3.22
electric load impedance
$\underline{Z}_L$
complex electric input impedance (consisting of a real and an imaginary part) to which the **hydrophone** unit output cable is connected or is intended to be connected

Note 1 to entry: The **electric load impedance** is expressed in ohms (Ω).

[SOURCE: IEC 62127-3:2007, 3.3, modified – In the definition, "**hydrophone** or **hydrophone assembly** output" has been replaced by "**hydrophone** unit output cable".]

3.23
elevation axis
line in the **source aperture plane** (measurement) or **transducer aperture plane** (design) that is perpendicular to the **azimuth axis** and the **beam axis**

SEE: Figure 1

[SOURCE: IEC 61828:2020, 3.48, modified – Notes to entry have been omitted.]

3.24
elevation plane
longitudinal plane containing the **elevation axis**

SEE: Figure 1

[SOURCE: IEC 61828:2020, 3.49, modified – The words "and the beam axis" have been deleted since this is already included in the definition of longitudinal plane.]

3.25
end-of-cable loaded sensitivity
$\underline{M}_L(f)$
<of a **hydrophone** or **hydrophone assembly**> quotient of the Fourier transformed **hydrophone** voltage-time signal $\mathcal{F}(u_L(t))$ at the end of any integral cable or output connector of a **hydrophone** or **hydrophone assembly**, when connected to a specified **electric load impedance**, to the Fourier transformed **acoustic pulse waveform** $\mathcal{F}(p(t))$ in the undisturbed free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_L(f) = \frac{\mathcal{F}(u_L(t))}{\mathcal{F}(p(t))} \qquad (3)$$

Note 1 to entry: The **end-of-cable loaded sensitivity** is a complex-valued parameter. Its modulus is expressed in units of volt per pascal (V/Pa), its phase angle is expressed in degrees, and represents the phase difference between the electrical voltage and the sound pressure.

3.26
end-of-cable loaded sensitivity level
$L_{M_\mathrm{L}}(f)$
<of a **hydrophone** or **hydrophone assembly**> twenty times the logarithm to the base 10 of the quotient of the modulus of the **end-of-cable loaded sensitivity** $|\underline{M}_\mathrm{L}(f)|$ to a reference sensitivity M_ref

$$L_{M_\mathrm{L}}(f) = 20\log_{10}\frac{|\underline{M}_\mathrm{L}(f)|}{M_\mathrm{ref}}\,\mathrm{dB} \tag{4}$$

Note 1 to entry: Commonly used values of the reference sensitivity M_ref are 1 V/µPa or 1 V/Pa.

Note 2 to entry: The **end-of-cable loaded sensitivity level** is expressed in decibels (dB).

3.27
end-of-cable open-circuit sensitivity
$\underline{M}_\mathrm{c}(f)$
<of a **hydrophone**> quotient of the Fourier transformed **hydrophone** open-circuit voltage-time signal $\mathcal{F}(u_\mathrm{c}(t))$ at the end of any integral cable or output connector of a **hydrophone** to the Fourier transformed **acoustic pulse waveform** $\mathcal{F}(p(t))$ in the undisturbed free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_\mathrm{c}(f) = \frac{\mathcal{F}(u_\mathrm{c}(t))}{\mathcal{F}(p(t))} \tag{5}$$

Note 1 to entry: The **end-of-cable open-circuit sensitivity** is a complex-valued parameter. Its modulus is expressed in units of volt per pascal (V/Pa), its phase angle is expressed in degrees, and represents the phase difference between the electrical voltage and the sound pressure.

3.28
external transducer surface
external transducer aperture
part of the surface of the **ultrasonic transducer** or **ultrasonic transducer element group** assembly that emits ultrasonic radiation into the propagation medium

SEE: Figure 1

Note 1 to entry: This surface is assumed to be accessible for measurements using a hydrophone in a chosen propagation medium (usually water).

Note 2 to entry: This surface is either directly in contact with the patient or is in contact with a water or liquid path to the patient.

[SOURCE: IEC 61828:2020, 3.52]

3.29
external transducer surface plane
external transducer aperture plane
plane that is orthogonal to the **beam axis** of the unsteered beam, or the axis of symmetry of the **azimuth plane** for an automatic scanner, and is adjacent physically to the **ultrasonic transducer** and **external transducer surface**

SEE: Figure 2

Note 1 to entry: If the **ultrasonic transducer** is flat, the plane is coplanar with the radiating surface of the **ultrasonic transducer**; if it is concave, the plane touches the periphery of the radiating surface; if it is convex, the plane is tangent to the centre of the radiating surface at the point of contact.

[SOURCE: IEC 61828:2020, 3.53]

3.30
far field
region of the field where $z > z_T$ aligned along the **beam axis** for planar non-focusing transducers

Note 1 to entry: In the **far field**, the sound pressure appears to be spherically divergent from a point on or near the radiating surface. Hence the pressure produced by the sound source is approximately inversely proportional to the distance from the source.

Note 2 to entry: The term **far field** is used in this document only in connection with non-focusing source transducers. For focusing transducers, a different terminology for the various parts of the transmitted field applies (see IEC 61828).

Note 3 to entry: If the shape of the transducer aperture produces several **transition distances**, the one furthest from the transducer is used.

3.31
hydrophone geometrical radius
a_g
radius defined by the dimensions of the active element of a **hydrophone**

Note 1 to entry: The **hydrophone geometrical radius** is expressed in metres (m).

[SOURCE: IEC 62127-3:2007, 3.8]

3.32
hydrophone
transducer that produces electric signals in response to pressure fluctuations in water

Note 1 to entry: A **hydrophone** is principally a passive device designed and built to respond to sound pressure.

Note 2 to entry: In some applications, a **hydrophone** is used as an active device to transmit sound.

[SOURCE: IEC 60050-801:2021, 801-32-26]

3.33
hydrophone assembly
combination of **hydrophone** and **hydrophone pre-amplifier**

[SOURCE: IEC 62127-3:2007, 3.10]

3.34
hydrophone pre-amplifier
active electronic device connected to, or to be connected to, a particular **hydrophone** and reducing its output impedance

Note 1 to entry: A **hydrophone pre-amplifier** requires a supply voltage (or supply voltages).

Note 2 to entry: The **hydrophone pre-amplifier** may have a forward voltage transmission factor of less than one, i.e. it need not necessarily be a voltage amplifier in the strict sense.

[SOURCE: IEC 62127-3:2007, 3.12]

3.35
instantaneous acoustic pressure
$p(t)$
pressure at a particular instant in time and at a particular point in an acoustic field, minus the ambient pressure

Note 1 to entry: **Instantaneous acoustic pressure** is expressed in pascals (Pa).

[SOURCE: IEC 60050-802:2011, 802-01-03]

3.36
instantaneous intensity
$I(t)$
acoustic energy transmitted per unit time in the direction of acoustic wave propagation per unit area normal to this direction at a particular instant in time and at a particular point in an acoustic field

Note 1 to entry: **Instantaneous intensity** is the product of **instantaneous acoustic pressure** and particle velocity. It is difficult to measure intensity in the ultrasound frequency range. For the measurement purposes referred to in this document and under conditions of sufficient distance from the **external transducer aperture** (at least one transducer diameter, or an equivalent transducer dimension in the case of a non-circular transducer) the **instantaneous intensity** can be approximated by the **derived instantaneous intensity.**

Note 2 to entry: **Instantaneous intensity** is expressed in units of watt per metre squared (W/m^2).

3.37
local area factor
F_a
square root of the ratio of the **source aperture area** to the **beam area** at the point of interest

$$F_a = \sqrt{\frac{A_{SAeff}}{A_b}} \tag{6}$$

Note 1 to entry: The relevant local **beam area**, A_b, is that for which the **pulse-pressure-squared integral** is greater than 0,135 (that is, 1/e^2) times the maximum value in the cross-section.

Note 2 to entry: If the beam profile is approximately Gaussian at the distance of interest and the area at the −6 dB level, $A_{b,6}$, is known, the local **beam area** can be calculated as $A_b = A_{b,6}/0,69$: (0,69 = 3 ln(10)/10): $F_a = \sqrt{\frac{0,69 A_{SAeff}}{A_{b,6}}}$.

[SOURCE: IEC TS 61949:2007, 3.11, modified – "source aperture" has been replaced by "source aperture area"; the formula for the general case has been added; the second sentence of the original definition has been moved to a Note 1 to entry; the third sentence of the original definition has been changed into a Note 2 to entry and provides more details and the symbol for the −6 dB **beam area** was changed to conform with Clause 4.]

3.38
local distortion parameter
σ_q
index which permits the prediction of nonlinear distortion of ultrasound for a specific **ultrasonic transducer**

$$\sigma_q = z\, p_m \frac{2\pi f_{awf}\, \beta}{\rho \cdot c^3} \frac{1}{\sqrt{F_a}} \tag{7}$$

where

z is the axial distance of the point of interest to the transducer face;

p_m is the **mean-peak acoustic pressure** at the point in the acoustic field corresponding to the **spatial-peak temporal-peak acoustic pressure**;

β is the nonlinearity parameter (β = 1 + B/2A = 3,5 for pure water at 20 °C);

f_{awf} is the **acoustic-working frequency**;

F_a is the **local area factor**.

Note 1 to entry: If the transmitting system comprises an internal standoff utilizing a water or water-equivalent propagation medium, the offset distance between the transducer element and the transducer face increases the actual path length z to be considered. The nominal distance between the **beam axis**'s intersection with the crystal and the transducer face can be used.

[SOURCE: IEC TS 61949:2007, 3.12, modified – The text of the definition has changed substantially, the formula however is unchanged; Note 1 to entry has been added.]

3.39
longitudinal plane
plane defined by the **beam axis** and a specified orthogonal axis

SEE: Figure 1

3.40
mean peak acoustic pressure
p_m
arithmetic mean of the **peak-rarefactional acoustic pressure** and the **peak-compressional acoustic pressure**

Note 1 to entry: **Mean peak acoustic pressure** is expressed in pascals (Pa).

[SOURCE: IEC TS 61949:2007, 3.13, modified – Note 1 to entry has been added.]

3.41
near field
region of the field where $z < z_T$ aligned along the **beam axis** for planar non-focusing transducers

Note 1 to entry: For circular planar transducers, this is at a distance less than $A_{ob}/\pi\lambda$, where A_{ob} is the **output beam area** and λ is the wavelength of the ultrasound corresponding to the **acoustic frequency**.

Note 2 to entry: If the shape of the transducer aperture produces several **transition distances**, the one closest to the transducer is used.

3.42
number of pulses per ultrasonic scan line
n_{pps}
number of acoustic pulses travelling along a particular **ultrasonic scan line**

Note 1 to entry: Here **ultrasonic scan line** refers to the path of acoustic pulses on a particular **beam axis** in **scanning modes** and **non-scanning modes**.

Note 2 to entry: This number can be used in the calculation of any ultrasound temporal average value from **hydrophone** measurements.

Note 3 to entry: The following shows an example of the **number of pulses per ultrasonic scanline** and the **number of ultrasonic scanlines** (shows the end of a frame):

1 2 3 4; 1 2 3 4; 1 2 3 4… n_{pps} = 1; n_{sl} = 4
1 1 2 2 3 3 4 4; 1 1 2 2 3 3 4 4; … n_{pps} = 2; n_{sl} = 4
1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4; 1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4; … n_{pps} = 4; n_{sl} = 4
1 1 2 2 3 3 4 4 1 1 1 2 2 2 3 3 3 4 4 4; 1 1 2 2 3 3 4 4 1 1 1 2 2 2 3 3 3 4 4 4; … n_{pps} = 5; n_{sl} = 4 (within one frame the pulses down each line may not occur contiguously)

Note 4 to entry: Within one frame, all scan lines possibly do not have the same n_{pps} value.
An example is: 1 2 2 3 3 4; 1 2 2 3 3 4; … avg n_{pps} = 1,5; max n_{pps} = 2; n_{sl} = 4

[SOURCE: IEC 61157:2007/AMD1:2013, 3.45 modified – the fourth example in Note 3 to entry has been corrected and the last example has been moved to a Note 4 to entry.]

3.43
number of ultrasonic scan lines
n_{sl}
quantity of **ultrasonic scan lines** that are excited during one **scan repetition period**

Note 1 to entry: This number can be used in the calculation of temporal average values for **scanning modes** from **hydrophone** measurements.

[SOURCE: IEC 61157:2007/AMD1:2013, 3.46]

3.44
offset distance
d_{offset}
distance between the **source aperture plane** and the **external transducer surface plane**, measured along the **beam axis**

SEE: Figure 2

Note 1 to entry: **Offset distance** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.90]

3.45
operating mode
mode of operation of a **system**

3.45.1
combined-operating mode
operating mode that combines more than one **discrete-operating mode**

Note 1 to entry: Examples of **combined-operating modes** are real-time B-mode combined with M-mode (B+M), real-time B-mode combined with pulsed Doppler (B+D), colour M-mode (cM), real-time B-mode combined with M-mode and pulsed Doppler (B+M+D), real-time B-mode combined with real-time flow-mapping Doppler (B+rD), i.e. flow-mapping in which different types of acoustic pulses are used to generate the Doppler information and the imaging information.

3.45.2
discrete-operating mode
operating mode of **medical diagnostic ultrasonic equipment** in which the purpose of the excitation of the **ultrasonic transducer** or **ultrasonic transducer element group** is to utilize only one diagnostic methodology

Note 1 to entry: Examples of **discrete-operating modes** are A-mode (A), M-mode (M), static B-mode (sB), real-time B-mode (B), continuous wave Doppler (cwD), pulsed Doppler (D), static flow-mapping (sD) and real-time flow-mapping Doppler (rD) using only one type of acoustic pulse.

3.45.3
inclusive mode
combined-operating mode having acoustic output levels (p_r and I_{spta}) less than those corresponding to a specified **discrete-operating mode**

3.45.4
non-scanning mode
operating mode that involves a sequence of ultrasonic pulses which give rise to **ultrasonic scan lines** that follow the same acoustic path

3.45.5
scanning mode
operating mode that involves a sequence of ultrasonic pulses which give rise to **ultrasonic scan lines** that do not follow the same acoustic path

3.46
output beam area
A_{ob}
area of the ultrasonic beam derived from the −12 dB **beam area** at the **external transducer aperture**

Note 1 to entry: For reasons of measurement accuracy, the −12 dB **output beam area** is derived from measurements at a distance chosen to be as close as possible to the face of the transducer, and, if possible, no more than 1 mm from the face.

Note 2 to entry: For contact transducers, this area can be taken as the geometrical area of the **ultrasonic transducer** or **ultrasonic transducer element group**.

Note 3 to entry: The **output beam area** is expressed in units of metre squared (m^2).

3.47
output beam dimensions
X_{ob}, Y_{ob}
dimensions of the ultrasonic beam (−12 dB **beamwidth**) in specified directions perpendicular to each other and in a direction normal to the **beam axis** and at the **external transducer aperture**

Note 1 to entry: For reasons of measurement accuracy, the −12 dB **output beam dimensions** is derived from measurements at a distance chosen to be as close as possible to the face of the transducer, and, if possible, no more than 1 mm from the face.

Note 2 to entry: For contact transducers, these dimensions can be taken as the geometrical dimensions of the **ultrasonic transducer** or **ultrasonic transducer element group**.

Note 3 to entry: **Output beam dimensions** are expressed in metres (m).

3.48
output beam intensity
I_{ob}
temporal-average power output divided by the **output beam area**

Note 1 to entry: **Output beam intensity** is expressed in units of watt per metre squared (W/m^2).

3.49
peak acoustic pressure
p_c (or p_+) or p_r (or p_-)
peak-compressional acoustic pressure or **peak-rarefactional acoustic pressure**

Note 1 to entry: **Peak acoustic pressure** is expressed in pascals (Pa).

3.50
peak-compressional acoustic pressure
p_c (or p_+)
maximum positive **instantaneous acoustic pressure** in an acoustic field or in a specified plane during an **acoustic repetition period**

Note 1 to entry: **Peak-compressional acoustic pressure** is expressed in pascals (Pa).

Note 2 to entry: The definition of **peak-compressional acoustic pressure** also applies to peak-positive acoustic pressure, which is also in use in literature.

3.51
peak-rarefactional acoustic pressure
p_r (or p_-)
maximum of the modulus of the negative **instantaneous acoustic pressure** in an acoustic field or in a specified plane during an **acoustic repetition period**

Note 1 to entry: **Peak-rarefactional acoustic pressure** is expressed using a positive number for the numerical value.

Note 2 to entry: **Peak-rarefactional acoustic pressure** is expressed in pascals (Pa).

Note 3 to entry: The definition of **peak-rarefactional acoustic pressure** also applies to peak-negative acoustic pressure, which is also in use in literature.

3.52
principal longitudinal plane
plane containing the **beam axis** and two points that define the minimum −6 dB **beamwidth**

SEE: Figure 1

Note 1 to entry: The selection of this axis is arbitrary for a circularly-symmetric transducer.

Note 2 to entry: For a HITU transducer with a hole in its centre within which is a diagnostic imaging transducer, this axis is aligned with the azimuth axis of the imaging transducer.

Note 3 to entry: For rectangular **ultrasonic transducers**, it is the plane parallel to their longest side.

[SOURCE: IEC 61828:2020, 3.110 modified – the reference to HITU transducers has been deleted in Note 1 to entry.]

3.53
pulse-average intensity
I_{pa}
quotient of the **pulse-intensity integral** to the **pulse duration** at a particular point in an acoustic field

Note 1 to entry: This definition applies to pulses and bursts.

Note 2 to entry: **Pulse-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.54
pulse duration
t_d
1,25 times the interval between the time when the time integral of the square of the **instantaneous acoustic pressure** reaches 10 % and 90 % of its final value

SEE: Figure 4

Note 1 to entry: The final value of the time integral of the square of the **instantaneous acoustic pressure** is the **pulse-pressure-squared integral**.

Note 2 to entry: **Pulse duration** is expressed in seconds (s).

3.55
pulse-intensity integral
pii
time integral of the **instantaneous intensity** at a particular point in an acoustic field integrated over the **acoustic pulse waveform**

Note 1 to entry: For measurement purposes referred to in this document, **pulse-intensity integral** is proportional to **pulse-pressure-squared integral**.

Note 2 to entry: The **pulse-intensity integral** is expressed in units of joule per metre squared (J/m^2).

3.56
pulse-pressure-squared integral
ppsi
time integral of the square of the **instantaneous acoustic pressure** at a particular point in an acoustic field integrated over the **acoustic pulse waveform**

Note 1 to entry: The **pulse-pressure-squared integral** is expressed in units of pascal squared times second (Pa^2s).

3.57
pulse repetition period
prp
time interval between equivalent points on successive pulses or tone-bursts of pulses comprising a **discrete operating mode**

Note 1 to entry: The **pulse repetition period** is expressed in seconds (s).

3.58
pulse repetition rate
prr
reciprocal of the **pulse repetition period**

Note 1 to entry: The **pulse repetition rate** is expressed in hertz (Hz).

3.59
reference centre
<of a **hydrophone**> point on, within or near a **hydrophone** about which its electro-acoustic characteristics are defined

Note 1 to entry: The **reference centre** often corresponds to the geometrical centre of a **hydrophone** active element, unless otherwise stated.

[SOURCE: IEC 60500:2017, 3.26, modified – The context <of a **hydrophone**> and the term "active element" in Note 1 to entry have been added. In the definition, the word "geometrical" has been deleted.]

3.60
RMS acoustic pressure
p_{RMS}
root-mean-square (RMS) of the **instantaneous acoustic pressure** at a particular point in an acoustic field

Note 1 to entry: The mean should be taken over an integral number of **acoustic repetition periods** unless otherwise specified.

Note 2 to entry: **RMS acoustic pressure** is expressed in pascals (Pa).

3.61
scan-area
A_s
<for automatic scanning systems> area on a specified plane (or surface) consisting of all points within the **beam area** of any beam passing through the surface during the scan

Note 1 to entry: The specified plane (or surface) follows the same shape as the **external transducer aperture**.

Note 2 to entry: The **scan-area** is expressed in units of metre squared (m^2).

3.62
scan plane
<for automatic scanning systems> plane containing all the **ultrasonic scan lines**

Note 1 to entry: Some scanning systems have the ability to steer the ultrasound beam in two directions. In this case, there is no **scan plane** that meets this definition. However, it might be useful to consider a plane through the major-axis of symmetry of the **ultrasonic transducer** and perpendicular to the transducer face (or another suitable plane) as being equivalent to the **scan plane**.

3.63
scan repetition period
srp
<for automatic scanning systems with a periodic scan sequence> time interval between identical points on two successive frames, sectors or scans

Note 1 to entry: In general, this document assumes that an individual scan line repeats exactly after a number of acoustic pulses. In case an **ultrasonic transducer** or **ultrasonic transducer element group** radiates ultrasound without any sequence of repetition, it will not be possible to characterize a scanned mode in the way described in this document. The approach described in Annex F can be useful when synchronization cannot be achieved.

Note 2 to entry: The **scan repetition period** is expressed in seconds (s).

3.64
scan repetition rate
srr
reciprocal of the **scan repetition period**

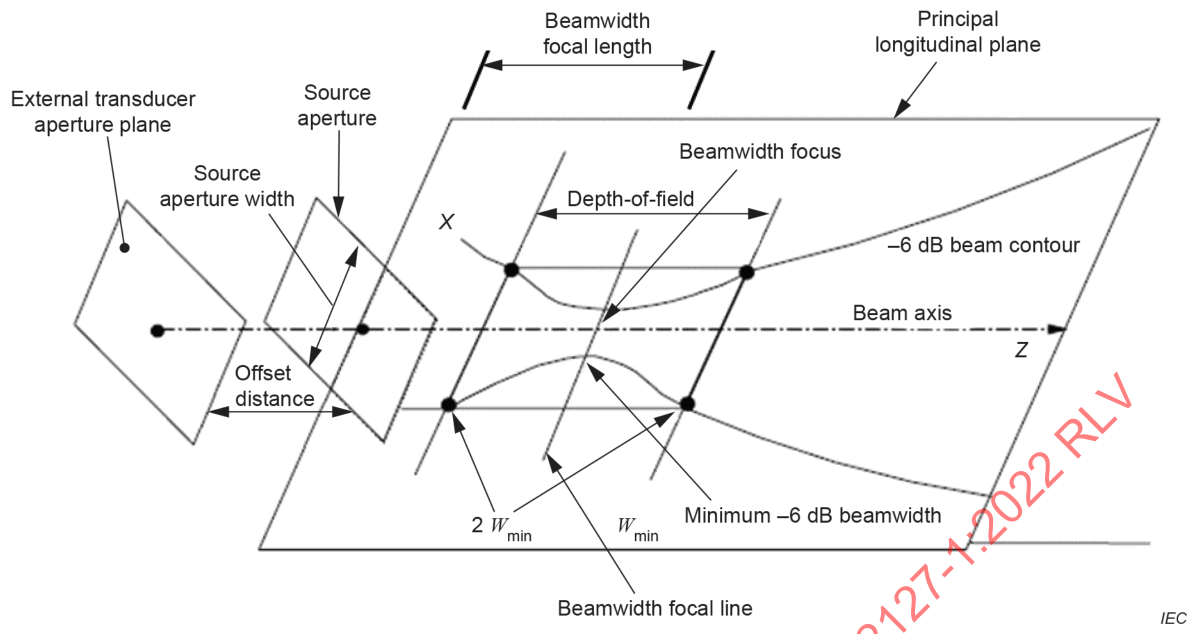
Note 1 to entry: The **scan repetition rate** is expressed in hertz (Hz).

3.65
source aperture area
A_{SAeff}
equivalent aperture area for an **ultrasonic transducer** of unknown characteristics, measured as the area inside the −20 dB **pulse-pressure-squared-integral** contour in the closest possible measurement plane (source aperture plane) to the **external transducer aperture**

SEE: Figure 2

Note 1 to entry: The nominal transmitting area of the source can be used for the calculation of the **local distortion parameter** σ_q in cases where there is a significant offset between the transducer crystal and the front face due to an internal standoff.

Note 2 to entry: **Source aperture area** is expressed in units of metre squared (m^2).



[SOURCE: IEC 61828:2020]

Figure 2 – Several apertures and planes for a transducer of unknown geometry

3.66
source aperture plane
closest possible measurement plane to the **external transducer surface plane** that is perpendicular to the **beam axis**

SEE: Figure 2

Note 1 to entry: If the **offset distance** is zero, the **source aperture plane** can be coincident with the **external transducer aperture plane**.

[SOURCE: IEC 61828:2020, 3.135]

3.67
source aperture width
L_{SA}
<in a specified **longitudinal plane**> greatest −20 dB **beamwidth** along the line of intersection between the designated **longitudinal plane** and the **source aperture plane**

SEE: Figure 2

Note 1 to entry: If a transducer is circularly-symmetric, a radial line scan is sufficient to determine the width.

Note 2 to entry: If a HITU transducer has a hole in its centre, the beginning and ending −20 dB points of the width are measured and noted with reference to the centre.

Note 3 to entry: **Source aperture width** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.136, modified – the reference to HITU transducers has been deleted in the Note 1 to entry.]

3.68
spatial-average pulse-average intensity
I_{sapa}
pulse-average intensity from one **ultrasonic transducer** or **ultrasonic transducer element group** averaged over the **beam-area** for that particular **ultrasonic transducer** or **ultrasonic transducer element group**

Note 1 to entry: A burst is also to be understood to be a pulse.

Note 2 to entry: **Spatial-average pulse-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.69
spatial-average temporal-average intensity
I_{sata}
temporal-average intensity averaged over the **scan-area** or **beam area** as appropriate

Note 1 to entry: **Spatial-average temporal-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.70
spatial-peak pulse-average intensity
I_{sppa}
maximum value of the **pulse-average intensity** in an acoustic field or in a specified plane

Note 1 to entry: **Spatial-peak pulse-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.71
spatial-peak RMS acoustic pressure
p_{spr}
maximum value of the **RMS acoustic pressure** in an acoustic field or in a specified plane

Note 1 to entry: **Spatial-peak RMS acoustic pressure** is expressed in pascals (Pa).

3.72
spatial-peak temporal-average intensity
I_{spta}
maximum value of the **temporal-average intensity** in an acoustic field or in a specified plane

Note 1 to entry: For systems in **combined-operating mode**, the time interval over which the temporal average is taken is sufficient to include any period during which scanning is not be taking place.

Note 2 to entry: **Spatial-peak temporal-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.73
spatial-peak temporal-peak acoustic pressure
p_{sptp}
larger of the **peak-compressional acoustic pressure** and the **peak-rarefactional acoustic pressure**

Note 1 to entry: **Spatial-peak temporal-peak acoustic pressure** is expressed in pascals (Pa).

3.74
spatial-peak temporal-peak intensity
I_{sptp}
maximum value of the **temporal-peak intensity** in an acoustic field or in a specified plane

Note 1 to entry: **Spatial-peak temporal-peak intensity** is expressed in units of watt per metre squared (W/m^2).

3.75
temporal-average intensity
I_{ta}
time-average of the **instantaneous intensity** at a particular point in an acoustic field

Note 1 to entry: The time-average is considered over an integral number of **acoustic repetition periods**.

Note 2 to entry: In principle, the **temporal-average intensity** is an average over a relatively long time interval. For ultrasonic medical diagnostic systems in **non-scanning modes**, the **instantaneous intensity** is averaged over one or more **pulse repetition periods**. For ultrasonic medical diagnostic systems in **scanning modes**, the **instantaneous intensity** is averaged over one or more **scan repetition periods** for a specified **operating mode**.

Note 3 to entry: **Temporal-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.76
temporal-peak acoustic pressure
p_{tp}
maximum value of the modulus of the **instantaneous acoustic pressure** at a particular point in an acoustic field

Note 1 to entry: **Temporal-peak acoustic pressure** is expressed in pascals (Pa).

3.77
temporal-peak intensity
I_{tp}
maximum value over time of the **instantaneous intensity** at a particular point in an acoustic field

Note 1 to entry: **Temporal-peak intensity** is expressed in units of watt per metre squared (W/m^2).

3.78
time-window-average intensity
$I_{w,\Delta t/s}(t)$
time-varying value of the **instantaneous intensity** averaged over a window of duration Δt

$$I_{w,\Delta t/s}(t) = \frac{1}{\Delta t} \int_{t-\Delta t/2}^{t+\Delta t/2} I(t')\,dt' \tag{8}$$

where

$I(t)$ is the **instantaneous intensity**;

Δt/s is the numerical value of the moving time window width in seconds;

t' is the variable of integration.

Note 1 to entry: The time varying **time-window-average intensity** for a time window width of 20 s, for instance, is denoted by $I_{w,20}(t)$.

Note 2 to entry: **Time-window-average intensity** is expressed in units of watt per metre squared (W/m^2).

3.79
transducer aperture area
A_{TA}
effective active area of an **ultrasonic transducer** in the **transducer aperture plane**

Note 1 to entry: **Transducer aperture area** is expressed in square metres (m^2).

[SOURCE: IEC 61828:2020, 3.145]

3.80
transducer aperture plane
plane that is orthogonal to the **beam axis** of the **unsteered beam** and is adjacent physically to the **ultrasonic transducer**

SEE: Figure 1

Note 1 to entry: If the **ultrasonic transducer** is flat, the plane is coplanar with the transmitting surface of the **ultrasonic transducer**; if it is concave, the plane touches the periphery of the transmitting surface; if it is convex, the plane is tangent to the centre of the transmitting surface at the point of contact.

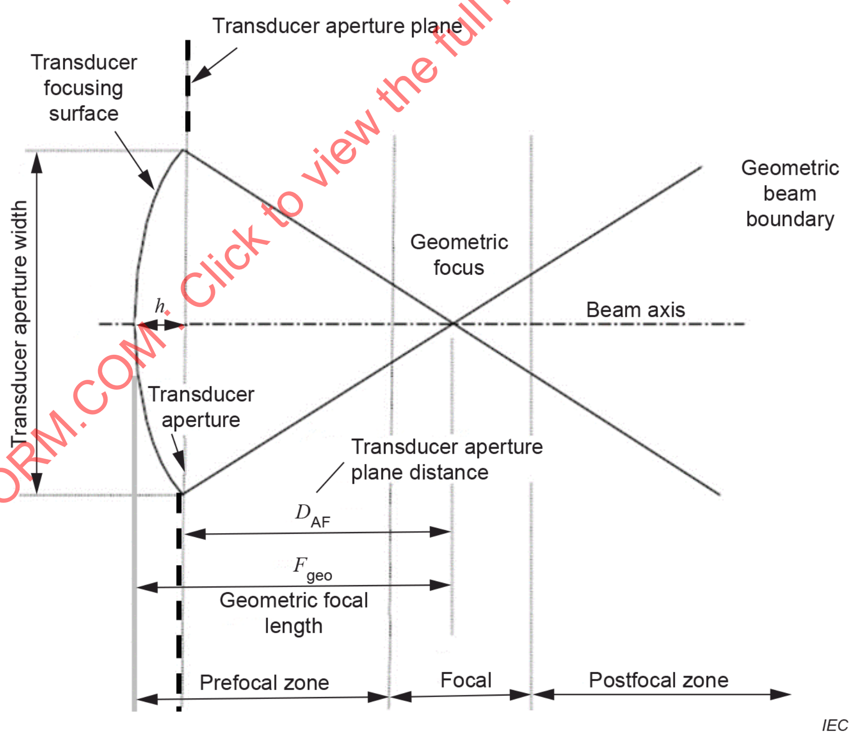
[SOURCE: IEC 61828:2020, 3.146]

3.81
transducer aperture width
L_{TA}
full width of the transducer aperture along a specified axis orthogonal to the **beam axis** of the unsteered beam at the centre of the transducer

SEE: Figure 3

Note 1 to entry: **Transducer aperture width** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.148, modified – The phrase "at the centre of the transducer" has been added to the definition.]



The radius of curvature is $D = D_{AF} + h$.

[SOURCE: IEC 61828:2020]

Figure 3 – Parameters for describing a focusing transducer of known geometry

3.82
transducer assembly
set of parts of **medical diagnostic ultrasonic equipment** comprising the **ultrasonic transducer** and/or **ultrasonic transducer element group**, together with any integral components, such as an acoustic lens or integral stand-off

Note 1 to entry: The **transducer assembly** is usually separable from the **ultrasound instrument console**.

3.83
transition distance
z_T
aperture area divided by π times the effective wavelength λ

[SOURCE: IEC 61828:2020, 3.153, modified – The words "effective wavelength" have been added to the definition.]

3.83.1
transition distance for design
z_{TD}
<for a given **longitudinal plane**> **transducer aperture area** A_{TA} of the **ultrasonic transducer** divided by π times the effective wavelength λ

$$z_{TD} = A_{TA}/(\pi\lambda) \tag{9}$$

Note 1 to entry: For design, for an unapodized **ultrasonic transducer** with circular symmetry about the **beam axis**, the **source aperture area** is πa_e^2, where a_e is the effective radius; therefore the **transition distance** is $z_T = a_e^2/\lambda$.

Note 2 to entry: For a spherically focusing transducer, the **transition distance** is approximately the same but more exactly it is $z_T = 2D^2\left(1-\sqrt{1-(a/D)^2}\right)\Big/\lambda$, where D is the radius of curvature.

Note 3 to entry: For design, for an unapodized rectangular **ultrasonic transducer** which has a **transducer aperture width**, L_{TA1}, in a specified **longitudinal plane**, the effective in-plane area is $(L_{TA1})^2$. Therefore, for this plane, the **transition distance** is $z_{T1} = (L_{TA1})^2/(\pi\lambda)$. The **transition distance** for the orthogonal **longitudinal plane** including the second **transducer aperture width** is $z_{T2} = (L_{TA2})^2/(\pi\lambda)$.

Note 4 to entry: For apodized transducers with a symmetric even apodization or weighting function W (normalized to a maximum value of one for the particle velocity distribution), the **transition distances** are the following.

For circularly symmetric transducers with an active radius a:

$$z_T = \left(\frac{2}{\lambda}\right)\int_0^a W(r)r\mathrm{d}r$$

For a rectangular transducer with a physical aperture length L in a given longitudinal plane, for example, xz:

$$z_T = \left(\frac{4}{\pi\lambda}\right)\left|\int_0^{L/2} W(x)\mathrm{d}x\right|^2$$

Note 5 to entry: For symmetric shapes other than the most common cases of circular symmetry and rectangular geometry, the same definition of **transition distance** can be used. For example, for apertures with n-fold symmetry (n > 2) such as hexagons and octagons, the **transition distance** in a symmetry plane perpendicular to a side is equal to the area of the aperture divided by ($\pi\lambda$). For annular arrays with several rings, the equivalent area is the total (all rings) area of the active aperture. For cases in which unique phasing is used, such as annular arrays with alternate phase shifts (0° or 180°) in addition to intended focusing or for cases of apertures with unusual shapes and phasing, three-dimensional diffraction computation is employed to determine the minimum beamwidth corresponding to the appropriate **transition distance**.

Note 6 to entry: **Transition distance for design** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.153.1, modified – Note 6 to entry has been omitted here.]

3.83.2
transition distance for measurement
z_{TM}
<for a given **longitudinal plane**> **source aperture area**, A_{SAeff}, of the **ultrasonic transducer** divided by π times the effective wavelength λ

$$z_{TM} = A_{SAeff}/(\pi\lambda) \tag{10}$$

Note 1 to entry: For measurements in each specified **longitudinal plane**, the **source aperture width** in that plane is used, or $z_{T1} = (L_{SA1})^2/(\pi\lambda)$; in the other orthogonal plane, $z_{T2} = (L_{SA2})^2/(\pi\lambda)$.

Note 2 to entry: **Transition distance for measurement** is expressed in metres (m).

[SOURCE: IEC 61828:2020, 3.153.2]

3.84
treatment head
assembly comprising an **ultrasonic transducer** and associated parts for local application of **ultrasound** to the patient

[SOURCE: IEC 60601-2-5:2009, 201.3.214, modified – A note in the original has been deleted.]

3.85
ultrasound instrument console
electronic unit to which the **transducer assembly** is attached

3.86
ultrasonic scan line
<for scanning systems> **beam axis** for a particular **ultrasonic transducer element group**, or for a particular excitation of an **ultrasonic transducer** or **ultrasonic transducer element** group

Note 1 to entry: In this document, **ultrasonic scan line** refers to the path of acoustic pulses and not to a line on an image on the display screen of a system.

Note 2 to entry: In general, this document assumes that an individual scan line repeats exactly after a given number of acoustic pulses. In case an **ultrasonic transducer** or **ultrasonic transducer element group** radiates ultrasound without any sequence of repetition, it will not be possible to characterize a scanned mode in the way described in this document. The approach described in Annex F can be useful when synchronization cannot be achieved.

Note 3 to entry: The case where a single excitation produces ultrasonic beams propagating along more than one **beam axis** is not considered.

3.87
ultrasonic scan line separation
s_s
<for automatic scanning systems> distance between the points of intersection of two consecutive **ultrasonic scan lines** of the same type and a specified line in the **scan plane**

Note 1 to entry: For this definition it is assumed that consecutive **ultrasonic scan lines** are spatially adjacent; this is not true for all types of scanning equipment.

Note 2 to entry: The **ultrasonic scan line separation** is expressed in metres (m).

3.88
ultrasonic transducer
device capable of converting electrical energy to mechanical energy within the ultrasonic frequency range and/or reciprocally of converting mechanical energy to electrical energy

3.89
ultrasonic transducer element
element of an **ultrasonic transducer** that is excited in order to produce an acoustic signal

3.90
ultrasonic transducer element group
group of elements of an **ultrasonic transducer** which are excited together in order to produce an acoustic signal

3.91
ultrasonic transducer element group dimensions
dimensions of the surface of the group of elements of an **ultrasonic transducer element group** which includes the distance between the elements, hence representing the overall dimensions

Note 1 to entry: **Ultrasonic transducer element group dimensions** are expressed in metres (m).

3.92
uncertainty
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

Note 1 to entry: See ISO/IEC Guide 98-3:2008, 2.2.3.

4 Symbols

a_{h}	**effective hydrophone size**
a_{g}	**hydrophone geometrical radius**
a_{t}	effective radius of a non-focusing **ultrasonic transducer**
a_{max}	maximum effective radius for a specific **hydrophone** application
arp	**acoustic repetition period**
$A_{\mathrm{b,6}}$, $A_{\mathrm{b,20}}$	**beam area** corresponding to −6 dB **beam area** and −20 dB **beam area**
A_{g}	geometrical area of an **ultrasonic transducer**
A_{ob}	**output beam area**
A_{s}	**scan-area**
A_{SAeff}	**source aperture area**
A_{TA}	**transducer aperture area**
BW	**bandwidth**
c	speed of sound in the medium (usually water)
C	end-of-cable capacitance of a **hydrophone**
C_{el}	parallel input capacitance of an electrical load
d_{offset}	**offset distance**
f_{awf}	**acoustic frequency**, **acoustic-working frequency**
f_{p}	**peak pulse** acoustic frequency
f_{t}	time average **acoustic frequency**
F_{a}	**local area factor**
I	**instantaneous intensity**
I_{ob}	**output beam intensity**

I_{pa}	**pulse-average intensity**
I_{sapa}	**spatial-average pulse-average intensity**
I_{sata}	**spatial-average temporal-average intensity**
I_{sppa}	**spatial-peak pulse-average intensity**
I_{ta}	**temporal-average intensity**
I_{tp}	**temporal-peak intensity**
I_{spta}	**spatial-peak temporal-average intensity**
I_{sptp}	**spatial-peak temporal-peak intensity**
$I_{w,\Delta t/s}$	**time-window-average intensity**
k	$2\pi/\lambda$
K_{sa}	spatial averaging correction factor
$L_{M_L}(f)$	**end-of-cable loaded sensitivity level**
$L_P(f)$	pressure level spectrum
$\underline{LP}(f)$	low-pass filtering function
L_{TA}	**transducer aperture width**
L_{SA}	**source aperture width**
$\underline{M}_c(f)$	**end-of-cable open-circuit sensitivity**
$\underline{M}_L(f)$	**end-of-cable loaded sensitivity**
n_{pps}	**number of pulses per ultrasonic scan line**
n_{sl}	**number of ultrasonic scan lines** per image for spatial distribution
p	**instantaneous acoustic pressure**
pii	**pulse-intensity integral**
$ppsi$	**pulse-pressure-squared integral**
p_m	**mean peak acoustic pressure**
p_{tp}	**temporal-peak acoustic pressure**
prr	**pulse repetition rate**
prp	**pulse repetition period**
p_{spr}	**spatial-peak RMS acoustic pressure**
p_{sptp}	**spatial-peak temporal-peak acoustic pressure**
p_{RMS}	**RMS acoustic pressure**
p_c (p_+)	**peak-compressional acoustic pressure**
p_r (p_-)	**peak-rarefactional acoustic pressure**
P	total ultrasonic power
P_{beam}	total power emitted by one acoustic scan line
R_{bh}	ratio of the −6 dB beamwidth to the effective **hydrophone** diameter
s_s	**ultrasonic scan line separation**
srp	**scan repetition period**
srr	**scan repetition rate**

t_d **pulse duration**

$\underline{U}_L(f)$ end-of-cable voltage for a **hydrophone**

v instantaneous particle velocity

w_6, w_{12}, w_{20} **beamwidth** (at −6 dB and −12 dB and −20 dB levels)

X_{ob}, Y_{ob} **output beam dimensions**

z distance between a **hydrophone** and an **ultrasonic transducer**

z_c **distance** z_c

z_{ppsi} **distance** z_{ppsi}

z_r **distance** z_r

z_{spta} **distance** z_{spta}

z_T **transition distance**

z_{TD} **transition distance for design**

z_{TM} **transition distance for measurement**

$\underline{Z}_h$ complex electric output impedance of a **hydrophone** or **hydrophone assembly**

$\underline{Z}_L$ **electric load impedance**

β nonlinearity parameter

θ angle of incidence of an ultrasonic wave with respect to the **hydrophone** axis

λ acoustic wavelength in a liquid

ρ density of the medium (usually water)

σ_q **local distortion parameter**

ω ($2\pi f_{awf}$) circular frequency

5 Measurement requirements

5.1 Requirements for hydrophones and amplifiers

5.1.1 Preface

In order to select a **hydrophone** and amplifier that is appropriate for the type of measurement to be undertaken, it shall be ensured that the selected devices conform with the following requirements. Requirements for **hydrophone** performance in this clause are either in addition to or supersede those for **hydrophones** in IEC 62127-3.

5.1.2 General

It is assumed throughout this document that a **hydrophone** is a device that responds to waterborne acoustic waves [see IEV 801-32-26] in such a way that the output voltage is proportional to the acoustic pressure. Generally, this relationship is frequency dependent; thus, if $\underline{M}_L(f)$ is the **end-of-cable loaded sensitivity** of a **hydrophone** (see 3.25 and Annex C), the **instantaneous acoustic pressure** $p(t)$ is related to the measured end-of-cable voltage $u_L(t)$ by

$$p(t) = \mathcal{F}^{-1}[\underline{U}_L(f) \,/\, \underline{M}_L(f)] \tag{11}$$

where

$\mathcal{F}^{-1}$ denotes the inverse Fourier transform;

$\underline{U}_L(f)$ is the Fourier transform result of $u_L(t)$.

NOTE 1 See 5.1.7.2 and Annex D to implement this method.

NOTE 2 For mathematical completeness, Formula (11) needs to include the real part operator, Re, on the right-hand side. However, for the type of spectra relevant here, the time domain data is not likely to comprise imaginary components with the exemption of a possible constant numerical residue, and thus Re is omitted in this formula throughout the document.

If the **hydrophone** or **hydrophone assembly** meets the requirements of a narrow-band approximation as specified in 5.1.7.1, then **instantaneous acoustic pressure** can be determined from Formula (12):

$$p(t) = u_L\,(t)\,/\,|\underline{M}_L(f_{awf})| \quad (12)$$

where

$|\underline{M}_L(f_{awf})|$ is the modulus of the **end-of-cable loaded sensitivity** of the **hydrophone** at the **acoustic-working frequency**.

5.1.3 Sensitivity of a hydrophone

When no **hydrophone pre-amplifier** is used, the sensitivity of the **hydrophone** shall refer to the **end-of-cable loaded sensitivity** and shall be determined for the particular electrical loading conditions (see 3.22).

When a **hydrophone pre-amplifier** is used, the sensitivity of the **hydrophone** shall refer to the **end-of-cable loaded sensitivity** which relates to the particular **hydrophone assembly**.

NOTE 1 The method outlined in IEC 62127-3 can be used for the determination of **end-of-cable loaded sensitivity** assuming the **end-of-cable open-circuit sensitivity of the hydrophone** is known.

NOTE 2 See Clause B.10 for tabulated examples of specification parameters.

5.1.4 Directional response of a hydrophone

The directional response of the **hydrophone** shall be known.

Symmetry of the directional response shall conform to IEC 62127-3.

NOTE There are two reasons to know the directional response of a **hydrophone**. First, it can be necessary as part of the field characterization procedures described in Annex B, in which case the directional response needs to be known at the appropriate **acoustic-working frequency**. Secondly, the directional response is used to derive the **effective hydrophone size**.

5.1.5 Effective hydrophone size

The **effective hydrophone size** shall be known and determined following the method described in IEC 62127-3.

5.1.6 Choice of the size of a hydrophone active element

5.1.6.1 General

The choice of the **effective hydrophone size** for a specific application shall be determined by consideration of the following.

The effective size of the element should ideally be comparable with or smaller than one quarter of the acoustic wavelength, so that phase and amplitude variations do not contribute significantly to measurement **uncertainties**.

It is not possible, because of the large range of types of **ultrasonic transducers**, to establish a simple relationship between the optimum effective element size of the **hydrophone** and parameters such as the **ultrasonic transducer** dimension, the acoustic wavelength and the distance from the **ultrasonic transducer**. However, in the **far field** it is reasonable to relax the above criterion. For circular **ultrasonic transducers**, the following criterion may be used as a guide to the determination of the maximum effective radius a_{max} of a **hydrophone** active element. a_{max} is given by Formula (13):

$$a_{max} = \frac{\lambda}{8a_1}\left(l^2 + a_1^2\right)^{1/2} \tag{13}$$

where

a_1 is the effective radius of the **ultrasonic transducer**;

l is the distance between the **hydrophone** and the **ultrasonic transducer** face;

λ is the acoustic wavelength corresponding to the **acoustic-working frequency**.

See [2] [1] and [3].

For a focused **ultrasonic transducer**, the above relationship may still be used.

For an **ultrasonic transducer** with a non-circular element, the above relationship may still be used by replacing a_1 by one half the maximum **ultrasonic transducer dimension** or **ultrasonic transducer element group dimension**.

Requirements of the size of the **hydrophone** active element are relaxed for measurements of ultrasonic fields generated by physiotherapy systems (see 8.3.1).

For representative experimental data, see [1].

5.1.6.2 Spatial averaging effect

The practical requirement of an adequate signal-to-noise ratio or other considerations can lead to the use of a **hydrophone** with an element size greater than that recommended above. In this case, care should be taken in interpreting measurements as a piezoelectric **hydrophone** is a phase sensitive detector that integrates the complex acoustic pressure over its active element.

When the **hydrophone** is translated from the position of maximum received signal in any direction normal to the **beam axis** by an amount equal to the **effective hydrophone size** element, the decrease in signal should be less than 1 dB. If this is not the case, corrections for spatial averaging should be made. See Annex E.

Improved corrections can also be made using diffraction corrections, see [2], [3], [4], [5].

The spatial averaging effect may also be addressed by spatial deconvolution of the **hydrophone** aperture as proposed in [6], [7], [8]. However, the method may suffer from signal-to-noise ratio issues in practical cases.

For nonlinear broadband **acoustic pulse waveforms**, the method of inverse spectral filtering as outlined in Clause E.2 should be applied to correct for spatial averaging.

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1 Numbers in square brackets refer to the Bibliography.

5.1.7 Bandwidth

5.1.7.1 Narrow-band approximation

Narrow-band approximations shall be considered as being appropriate whenever the **local distortion parameter** is less than 0,5 (see 7.2.4).

In this case, it is sufficient to consider the sensitivity value at the **acoustic-working frequency** as being representative of the sensitivity value at all frequencies of interest.

NOTE 1 When measuring narrow-band acoustic signals, it is assumed that all the significant frequency components within the signal are located at frequencies close to the **acoustic-working frequency**. In this case, there will be little variation in the **end-of-cable loaded sensitivity** of the **hydrophone**.

NOTE 2 The simplifying assumption given above can also be used when measuring acoustic fields with a broader frequency content provided that the **end-of-cable loaded sensitivity** of the **hydrophone** shows only limited variations over the frequency range necessary to accurately represent the acoustic signal.

If the value of the **local distortion parameter** exceeds 0,5 (see 7.2.4), then the **end-of-cable loaded sensitivity level** of the **hydrophone** or **hydrophone assembly** shall vary by less than ±3 dB over the frequency range (f) from one octave below to three octaves above the **acoustic-working frequency**, where the 0 dB reference point is located at the **acoustic-working frequency**, f_{awf}. That is, for

$$f_{\text{awf}} / 2 \le f \le 8\, f_{\text{awf}} \tag{14}$$

$$L_{M_{\text{L}}}\left(f_{\text{awf}}\right) - 3\ \text{dB} \le L_{M_{\text{L}}}\left(f\right) \le L_{M_{\text{L}}}\left(f_{\text{awf}}\right) + 3\ \text{dB} \tag{15}$$

where $L_{M_{\text{L}}}\left(f\right) = 20\log_{10}\dfrac{\left|\underline{M}_{\text{L}}\left(f\right)\right|}{M_{\text{ref}}}\text{dB}$ and $M_{\text{ref}} = 1\dfrac{\text{V}}{\text{Pa}}$.

NOTE 3 There is scientific justification for using an extended range $f_{\text{awf}}/16 \le f \le 8f_{\text{awf}}$ (i.e. four octaves below to three octaves above f_{awf}), based on [9] and [10] (see also Annex A). However, experimentally determined **hydrophone** calibration data is available for a limited **bandwidth** only, for instance from 1 MHz to 100 MHz. To judge whether the narrow-band approximation is appropriate according to Formulas (14) and (15), **hydrophone** frequency response extrapolation can be applied as an alternative method in the same way as described in 5.1.7.2.2 including Notes 1, 2 and 3, and Annex D for broadband measurements, if necessary. That is, extrapolation of $\underline{M}_{\text{L}}(f)$ can be used to cover frequencies f outside the calibration range available, at maximum below half of the **acoustic-working frequency** towards zero and above the lesser of four times the **acoustic-working frequency** or 100 MHz towards the Nyquist frequency f_{Nyquist}, e.g. for $0 \le f < f_{\text{awf}}/2$ and for min [4 f_{awf}, 100 MHz] $< f \le f_{\text{Nyquist}}$. Details on considerations for appropriate extrapolation are provided in D.4.2.

If the narrow-band approximation requirements are not fulfilled the broadband measurement method of 5.1.7.2 shall be followed.

If the broadband measurement method of 5.1.7.2 is implemented in the measurement system, it may be used for all situations including those covered by the narrow-band approximation requirements.

Measurements performed in conformity with the first edition of IEC 62127-1 may have considered frequency contributions up to 40 MHz only. The changed requirements of this second edition do not imply that such measurements of the past shall be repeated for output measurements on equipment already characterized in conformity with the first edition. If necessary, the systematic error of the limited bandwidth may in such cases then be attributed by an additional **uncertainty** contribution.

NOTE 4 See 8.2.4 for specific consideration of diagnostic equipment of low acoustic output.

5.1.7.2 Broadband measurements

5.1.7.2.1 General

In case the narrow-band approximation requirements cannot be met, the **uncertainty** in the measurement can become unacceptably large due to limited bandwidth and frequency dependent sensitivity variation of the **hydrophone.** Voltage-to-pressure conversion shall then be performed using the frequency-dependent sensitivity of the **hydrophone** and the frequency content of the **acoustic pulse waveform**. The measurement method based on deconvolution of the acquired waveform with the **hydrophone** response as described here in 5.1.7.2 and in Annex D produces more accurate results. For performing deconvolution, specific aspects of hydrophone calibration data conditioning, regularization filtering of signal spectra, and **uncertainty** determination shall be considered in accordance with 5.1.7.2.2, 5.1.7.2.3 and 5.1.7.2.4.

5.1.7.2.2 Deconvolution bandwidth

Application of Formula (11) to determine the **acoustic pulse waveform** requires the complex division of the voltage spectrum $\underline{U}_{\mathrm{L}}(f)$ by the sensitivity $\underline{M}_{\mathrm{L}}(f)$. For this operation data sets must match, e.g. the frequency increment and range of both spectra must be the same. The frequency increment of $\underline{U}_{\mathrm{L}}(f)$ depends on the length of the acquired **acoustic pulse waveform** (including zero padding if applicable) and the frequency range extends from 0 to the Nyquist frequency associated with the sample rate used. Experimentally obtained **hydrophone** calibration data $\underline{M}_{\mathrm{L}}(f)$, however, may provide different frequency increments and ranges. If necessary, calibration data can be interpolated between consecutive sensitivity data points available for the **hydrophone** (see Annex D). If necessary, extrapolation of $\underline{M}_{\mathrm{L}}(f)$ may be used to cover frequencies f outside the calibration range available, at maximum below half of the **acoustic-working frequency** towards zero and above the lesser of four times the **acoustic-working frequency** or 100 MHz towards the Nyquist frequency f_{Nyquist}, e.g. for $0 \leq f < f_{\mathrm{awf}}/2$ and for min $[4\, f_{\mathrm{awf}}$, 100 MHz$] < f \leq f_{\mathrm{Nyquist}}$. Details on considerations for appropriate extrapolation are provided in D.4.2.

NOTE 1 The maximum lower limit of 100 MHz for extrapolating at higher frequencies in the above requirement assumes availability of hydrophone calibration certificates up to 100 MHz at the time this document is published. If only a lower upper limit is available at this time, then that limit can be used instead for practicability.

NOTE 2 Secondary pulse calibration techniques have been developed [11], [12] and can be applied by the hydrophone user to determine the sensitivity of the individual hydrophone in frequency ranges where calibration service is not available. The same techniques can be used, in general, for hydrophone calibration data extrapolation, and to check conformity with the narrow-band approximation through Formulas (14) and(15).

NOTE 3 For some types of hydrophones, the variation of sensitivity at higher frequency can possibly be predicted from calibration data obtained at lower frequencies. For example, above the resonance frequency of a membrane hydrophone, the sensitivity is likely to follow a predictable trend. In such cases, the sensitivity prediction can be used in place of direct measurements so long as the **uncertainty** in the prediction is accounted for, based on calibration measurements of similar hydrophones throughout the frequency range where the prediction is used.

5.1.7.2.3 Regularization

Deconvolution is mathematically speaking an ill-posed inverse problem, which in the discrete time domain results in an ill-conditioned estimation problem [13], [14]. For instance, at very high frequency the acquired **hydrophone** signal may still comprise some noise contribution but the sensitivity may be close to zero. Formula (11) then leads to a large impact of such noise within the deconvolution, see Annex D for a waveform example. To obtain waveforms with acceptable overall noise, in general, appropriate low-pass filtering is necessary; this also reduces the occurrence of Gibbs oscillations. Including such a regularization, Formula (11) is then extended towards

$$p(t) = \mathcal{F}^{-1}\left(\underline{LP}(f)\cdot\frac{\underline{U}_{\mathrm{L}}(f)}{\underline{M}_{\mathrm{L}}(f)}\right) \tag{16}$$

where $\underline{LP}(f)$ denotes the complex-valued low-pass filtering function. Different filter functions can be used for **hydrophone** signal deconvolution [14], [15], [16], [17], [18], [19], [20], [21]. Since any low-pass filtering induces additional **bandwidth** limitation and hence possibly cutting of peak pressure parts of the waveform, the filter cut-off frequency shall be kept as large as possible while still providing enough noise suppression to achieve reasonable **uncertainties** for waveform parameters. The −3 dB cut-off frequency of the low-pass filtering shall be 8-times the **acoustic-working frequency** f_{awf} determined from the pressure spectrum without low-pass filtering or higher.

NOTE 1 In measurement situations with stable pulse repetition, high-frequency noise suppression can be improved by increasing signal averaging.

NOTE 2 In general, **bandwidth** reduction of nonlinearly distorted ultrasonic waveforms through additional low-pass filtering will affect the peak compressional pressure stronger than the peak rarefactional pressure and derived intensity data.

NOTE 3 For high amplitude nonlinearly distorted waveforms of high intensity therapeutic ultrasound or lithotripsy comprising up to 100 harmonics, cut-off frequencies larger than 8-times the **acoustic-working frequency** are needed to avoid cutting of the peak compressional waveform parts and excessive systematic **uncertainty** contribution of the regularization. Specifications are provided in 8.3.2.

NOTE 4 A good choice for the numerical filter type sufficient in many applications is of the form $\underline{LP}(f) = 1\Big/\left(1+\frac{if}{f_{\mathrm{g}}}\right)^2$ with $i = \sqrt{-1}$ and f_{g} denoting the −6 dB corner frequency. The −3 dB corner frequency then is approximately f_{g} /1,555 [17].

NOTE 5 In principle, the regularization filter and cut-off frequency choice can be supported by optimizing the overall **uncertainty** of the deconvolved waveform including the partly competing noise and regularization components [14].

NOTE 6 Of the acoustic parameters listed in 7.2.1, the **peak compressional acoustic pressure** is most likely to be affected by the choice of the regularization filter.

5.1.7.2.4 Uncertainty estimation for broadband measurement method

Due to the application of Fourier transforms and inverse Fourier transforms, regularization filtering, as well as complex-valued **hydrophone** calibration data, the **uncertainty** estimation for the broadband measurement method may appear less straightforward than in other situations. However, a GUM-compliant **uncertainty** evaluation (ISO/IEC Guide 98-3 and ISO/IEC Guide 98-3/Suppl.2 [22]) can be performed utilizing closed formulae for the propagation of **uncertainties** when discrete Fourier and inverse Fourier transforms are applied, and an open-source software tool GUM2DFT[2] is available [21]. The method enables, for instance, to propagate to the time domain the frequency dependent **uncertainties** of the **hydrophone** calibration data provided for modulus and phase in the frequency domain.

The introduction of additional numerical low-pass filtering for regularizing the deconvolution problem introduces an additional **uncertainty** contribution to the measurement and data evaluation procedure. The impact of the induced systematic error can be quantitatively assessed, for instance, by considering a continuous upper bound function in the frequency domain for the pressure magnitude spectrum based on a simple one-parametric basis functions approach and incorporating additional prior knowledge, like monotonously decreasing spectral components with frequency expected for nonlinearly distorted **acoustic pulse waveforms**, and typical signature of high frequency noise in distinction to waveform signal contribution [14].

2 This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

5.1.8 Linearity

The linear response, as defined in IEC 62127-3, should extend to 5 MPa.

The upper limit of known dynamic range shall be stated, in particular if below 5 MPa.

5.1.9 Hydrophone signal amplifier

5.1.9.1 General

Hydrophone amplifiers shall meet the following performance requirements.

5.1.9.2 Requirements for all amplifiers

The amplifier gain shall allow the **hydrophone assembly** to meet the requirements given in 5.1.7.

The sensitivity level shall not vary by more than 0,5 dB per 100 kHz frequency increment inside the stated **bandwidth**. The requirement can be verified using an appropriate representation of the frequency response that resolves all important details of the frequency dependence.

The linearity with input signal over a dynamic range of 50 dB shall be ±0,3 dB.

The spectral noise measured generated by the **hydrophone assembly** shall be sufficiently low to allow measurements to be performed with an adequate signal-to-noise ratio for any frequency within the **bandwidth** considered.

The following performance parameters shall be specified:

– the gain as a function of frequency;

– the input impedance as a function of frequency, either the real and imaginary components ($\underline{Z}_L$) (see 3.22), or the equivalent parallel resistive and capacitive components;

– the output impedance.

5.1.9.3 Additional requirements for differential amplifiers

The impedance requirements given above shall apply except that the impedance is measured between the two active inputs.

The common mode rejection shall be at least 40 dB (referred to the input) over the frequency range one octave below to two octaves above f_{awf}. See [23], [24].

5.1.10 Hydrophone cable length and amplifiers

A connecting cable of a length and characteristic impedance which ensures that electrical resonance in the connecting cable does not affect the defined **bandwidth** of the **hydrophone** or **hydrophone assembly** shall be chosen. The cable shall also be terminated appropriately.

To minimize the effect of resonance in the connecting cable, the length of the **hydrophone** cable (in metres) shall be much less than $50/(f_{awf} + BW_{20})$, where f_{awf} is the **acoustic-working frequency** in MHz and BW_{20} is the −20 dB **bandwidth** in MHz of the **hydrophone** signal. In most cases a cable length of ≤ 15 cm is usually adequate (see [25]).

NOTE 1 Attention is to be paid to the appropriateness of the output impedance of the **hydrophone**/amplifier in relation to the input impedance of the connected measuring device.

NOTE 2 Methods that can be used to correct the effects of finite **bandwidth** of the **hydrophone**/amplifier on waveforms suffering distortion from nonlinear propagation are given in Annex D.

5.2 Requirements for positioning and water baths

5.2.1 General

There are various possible systems that may be used to mount the **ultrasonic transducer** and **hydrophone**. The general performance requirements for such systems are specified here, and these are considered as optimum for the purposes of this document. Alternative positioning systems may be used providing equivalence with those described in this subclause is demonstrated.

Annex J shows a simple configuration of tank, **ultrasonic transducer** and **hydrophone** intended to show only the coordinate axes and degrees of freedom referred to in this document.

5.2.2 Positioning systems

5.2.2.1 Transducer positioning

The **ultrasonic transducer** under test shall be supported using a positioning system such that its face is fully immersed in the water bath and at a distance from any adjacent surface, for instance, a water/air interface, so that reflected ultrasound from this surface does not interfere with the main received signal. For the situation when the surface is parallel to the **beam axis**, the following criteria shall be satisfied.

If z is the distance between the active element of a **hydrophone** and the face of an **ultrasonic transducer** and t is the time between the arrival of the direct pulse at the **hydrophone** and the end of the measurement acquisition period, then the minimum distance, h, between the **beam axis** and the reflecting surface shall be determined from Formula (17):

$$(z^2 + 4h^2)^{1/2} - z > c\,t \tag{17}$$

It is preferable to immerse the transducer and not to use a membrane between the face of the **ultrasonic transducer** and the water bath. If, however, a membrane is needed, then the membrane should be as thin as practicable and should be kept as close to the front surface of the **ultrasonic transducer** as is possible. Close acoustic coupling should be ensured by using a water-based coupling agent, taking care to exclude bubbles of air. Measurements of acoustic parameters should be corrected for transmission loss of the membrane.

5.2.2.2 Hydrophone positioning

The **hydrophone** shall be set up in the coordinate positioning system such that the direction of maximum sensitivity of the **hydrophone** is approximately parallel to the anticipated direction of the **beam axis** of the **ultrasonic transducer** to be measured.

NOTE To avoid effects on the measurements made on continuous wave fields due to reflection of ultrasound from the surface of membrane **hydrophones**, the **hydrophone** can be tilted. Tilting ensures that the reflected ultrasound either does not interfere significantly with the transducer or is not subsequently reflected from the transducer face, producing interference effects. Two methods used to determine the rotation required are described in Annex B.

5.2.2.3 Spatial positioning

The **hydrophone** and/or the **ultrasonic transducer** shall be supported from a positioning system to allow them to be positioned relative to each other at any desired point within a space with the following degrees of freedom:

a) spatial positioning along three orthogonal axes (named x, y and z), one (designated the z-axis) being the **beam axis** of the active element of the **ultrasonic transducer**;

b) to be able to reproduce positions, all translation and rotation systems should be provided with position indicators;

c) the repeatability of positioning should be 0,10λ or 0,05 mm, whichever is smaller.

NOTE 1 After alignment, the z-axis is expected to be parallel to the **beam axis** of the **ultrasonic transducer**.

NOTE 2 It is possible to relax the requirement of the reproducibility for many measurements. A reasonable basis is to relate the precision of the positioning system to the diameter of the active element of the **hydrophone**. In the direction perpendicular to the direction of propagation of the ultrasound, a precision equivalent to 10 % of the diameter of the active element of the **hydrophone** is usually adequate, while in a direction parallel to the propagation direction a precision equivalent to the diameter of the active element is usually adequate.

5.2.3 Water bath

5.2.3.1 General

The size of the measurement vessel shall be such that the **ultrasonic transducer** and **hydrophone** can be moved relative to each other by an amount large enough to permit the active element of the **hydrophone** to be positioned at any point in the acoustic field at which measurements are required.

Means shall be incorporated to minimize effects on the measurement of reflection from any part within the water bath or the walls (see also 5.2.3.2).

In a direction parallel to the **beam axis** for non-automatic scanning systems or the symmetry axis of the **azimuth plane** for automatic scanning systems, the wall of the water bath should be at a distance from the **ultrasonic transducer** which is significantly greater (30 % to 100 %) than the maximum separation distance between the **ultrasonic transducer** and the **hydrophone**.

In a direction perpendicular to the **beam axis** for non-automatic scanning systems or the symmetry axis of the **azimuth plane** for automatic scanning systems, the wall of the water bath should be at a distance which is significantly greater (30 % to 100 %) than the maximum distance of the **hydrophone** from the **beam axis** in the case of non-automatic scanning systems, or from an extreme **scan line** in the case of automatic scanning systems.

NOTE 1 The size of the **hydrophone** also needs consideration; for membrane **hydrophones**, extra width in the direction perpendicular to the **beam axis** might be needed.

NOTE 2 The criteria for the choice of the size of the water bath referred to above are adequate for **pulse durations** less than 10 µs. For longer **pulse durations**, refer to 5.2.2.1 and [26].

5.2.3.2 Lining material

The measurements should be performed under conditions that approximate an acoustic free field. In the case of **ultrasonic transducers** excited under continuous wave conditions, acoustic absorbers should be placed to intercept as much of the ultrasound incident on the walls of the water bath as is possible. For pulsed **ultrasonic transducers**, and when techniques using gated signals are employed for detection of the **hydrophone** signal, it is not essential to use acoustic absorbers. However, it is often advisable to place absorbers on the walls of the water bath at positions so that they intercept the main incident acoustic field from the **ultrasonic transducer**.

The following tests may be used to determine the necessity for acoustic absorbers.

The criterion that may be applied is that acoustic absorbers should be used if reflected ultrasound increases the general background noise level of the **hydrophone** signal uniformly or if spurious **hydrophone** signals are detected in the vicinity of the main received signal.

A convenient test for the presence of spurious signals consists in changing the distance between the **ultrasonic transducer** and the **hydrophone** while observing the signal with an oscilloscope. Some spurious signals are observed to move at least twice the speed of the directly received signal, others are received in an incorrect time window when comparing the **ultrasonic transducer** to **hydrophone** distance. This test is possible only on pulsed systems.

With continuous wave excitation, it is necessary to observe phase changes and distortion of the main signal when the **ultrasonic transducer** is moved. A partial standing wave pattern may also be observed in many cases.

The free field conditions will be met sufficiently when the overall echo is reduced by more than 25 dB. Various methods may be used to check the conformity of the echo reduction of the tank lining materials used, with this subclause. The procedures described in IEC TS 63081 can be applied to check the absorbing or scattering materials.

5.2.3.3 Water quality

For measurements in high pressure fields or on high power continuous wave excited **ultrasonic transducers**, cavitation effects can be significant, and, in this case, degassed water should be used (see Annex G for guidance).

The water should be distilled or de-ionized water at a known temperature. When a single-layer, electrically unshielded membrane [polyvinylidenefluoride (PVDF)] **hydrophone** is used, the electrical conductivity of the water should be less than 5 μS cm^{-1}.

5.3 Requirements for data acquisition and analysis systems

The transfer characteristics of the data acquisition and analysis system shall be adequate to ensure that, when used in combination with the **hydrophone**, pre-amplifier and amplifier, the requirements of 5.1.6 to 5.1.9 are met for the combination.

5.4 Recommendations for ultrasonic equipment being characterized

If the scanning in automatic scanning systems can be "frozen", appropriate acoustic measurements should be undertaken to ensure that there is no significant variation between a "frozen" beam and a scanning beam.

NOTE 1 This exercise is not trivial and depends on the type of scanning system. Also, true determination of temporal average parameters is not possible for a "frozen" beam.

If an electrical signal synchronized to the excitation of the **ultrasonic transducer** or **ultrasonic transducer element group** is not available, alternative methods may be used to obtain such a trigger signal.

NOTE 2 Such alternative methods include the use of an external electromagnetic pick-up coil or an auxiliary acoustic sensor placed in the ultrasonic field. See [27], [28], [29].

In case an **ultrasonic transducer** or **ultrasonic transducer element group** radiates ultrasound without any sequence of repetition, it will not be possible to synchronize the measurement system in the way described in this document. A subset of acoustic measurements, mostly related to safety aspects, is described in Annex F and may be useful when synchronization cannot be achieved.

Any system that controls the acoustic output of the **ultrasonic transducer** as a result of changing acoustic impedance should be switched off. In case this cannot be achieved, an additional measurement **uncertainty** should be taken into account.

6 Measurement procedure

6.1 General

The procedures described in Clause 6 and in Clause 7 are those that are particularly suitable for the characterization of ultrasonic fields using piezoelectric **hydrophones**. Other procedures based on the use of piezoelectric **hydrophones** may be employed provided equivalence with the techniques described in Clause 6 is demonstrated.

6.2 Preparation and alignment

6.2.1 Preparation

It may be necessary to seal various parts of the **ultrasonic transducer** to prevent ingress of water, especially around the cable entry point if the whole of the device is immersed. The manufacturer's advice should be sought.

Prior to use, the surfaces of the **ultrasonic transducer** and the **hydrophone** should be checked for contamination. If this is present, the surfaces should be cleaned according to the manufacturer's instructions. Any special precautions should be followed for the reliable use of **hydrophones** or **transducers** which may be specified by the manufacturer or which may have been found necessary by the user, such as immersion of a **hydrophone** for a certain time before use.

On insertion of both the **ultrasonic transducer** and the **hydrophone** in the water, care should be taken to ensure that all air bubbles are removed from the active faces. Checks should be made during the course of the measurements to ensure bubbles do not appear.

6.2.2 Aligning an ultrasonic transducer and a hydrophone

The z-axis of the **hydrophone**, which is the direction of maximum sensitivity, shall be aligned such that it is parallel to the direction of propagation of the ultrasound. A proper alignment procedure is given in IEC 61828.

6.3 Measurement

Make the measurements with an appropriate **hydrophone assembly**. Carry out observation at any point for long enough that a fully representative part of the acoustic signal is sampled. Typically, this would be less than one second.

Ensure that the **bandwidth**, sampling rate and/or temporal resolution of the acquisition system are sufficient to accurately represent the **hydrophone** signal.

NOTE 1 New technology oscilloscopes and digital capture cards are now available which allow extremely long record lengths to be captured and analysed. In general, use of such a device is likely to be the most flexible way to determine all the necessary parameters.

NOTE 2 Since it is no longer assumed that the acoustic signal will repeat, equivalent-time sampling is not possible and, consequently, the single-shot digital **bandwidth** will need to be sufficient to accurately represent the **hydrophone** signal.

6.4 Analysis

6.4.1 Corrections for restricted bandwidth and spatial resolution

Corrections shall be applied if the measurements are affected by a limited **bandwidth** (see 5.1.7) or cable resonances (see 5.1.10). If the narrow-band requirements (see 5.1.7.1) are not fulfilled the deconvolution method shall be applied (see 5.1.7.2).

Corrections shall be applied if the measurements are affected by spatial averaging effects as identified in 5.1.6.2. Corrections shall be made following the methods given in Annex E.

6.4.2 Uncertainties

In evaluating and expressing the **uncertainty** in the calibration, the guidance provided by ISO/IEC Guide 98-3:2008 [see Clause 2] shall be followed.

More guidance on assessment of **uncertainties** is given in Annex I.

7 Beam characterization

7.1 General

Table 1 provides a guide to the acoustic parameters that may be used to specify the acoustic output of various types of medical ultrasonic equipment.

Table 1 – Acoustic parameters appropriate to various types of medical ultrasonic equipment

Equipment type		Primary pressure parameters	Derived intensity parameters	Other parameters
Pulse-echo	– static	1, 2	4 to 6	7, 8, 10 to 16, 18 to 20
	– auto scanning	1, 2	4 to 6	7, 8, 10 to 20
Doppler	– vascular	1[a], 2	4 to 6	7, 10, 11, 14, 18, 19
	– foetal heart	1[a], 2	4 to 6	7, 10, 11, 14, 18, 19
	– pulsed	1, 2	4 to 6	7, 8, 10 to 16, 18 to 20
Therapy (physical)	– continuous	1[a], 2, 3	5, 6	7, 9, 12, 14, 18, 19
	– tone-burst	1[a], 2, 3	4 to 6	7, 9, 12, 14 to 16, 18, 19

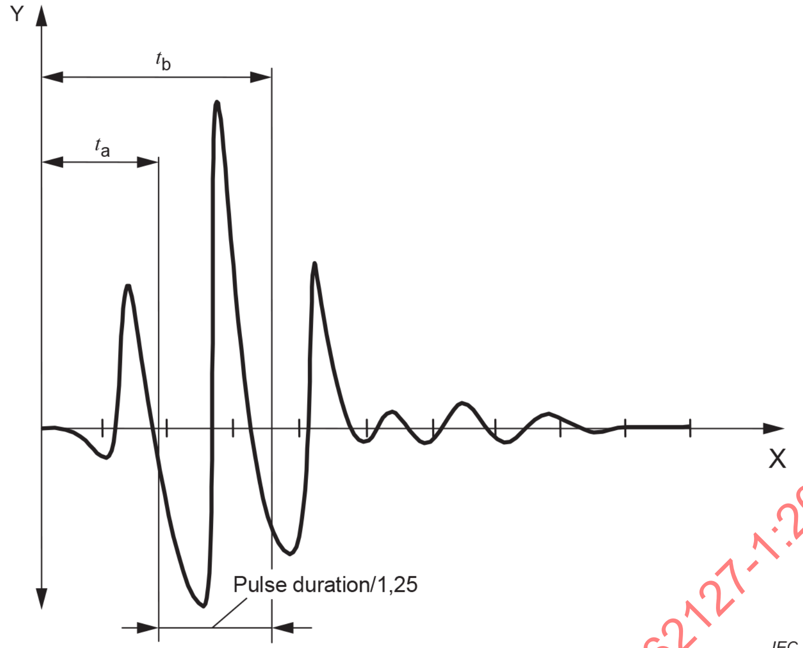
NOTE Key to table as follows:

	Clause			Clause	
1	3.50	Peak-compressional acoustic pressure	8	3.11	Beamwidth
2	3.51	Peak-rarefactional acoustic pressure	9	3.7	−20 dB beam area
3	3.60	RMS acoustic pressure	10	3.7	−6 dB beam area
4	3.70	Spatial-peak pulse-average intensity	11	3.47	−12 dB output beam dimensions
5	3.72	Spatial-peak temporal-average intensity	12	3.38	Local distortion parameter
6	3.69	Spatial-average temporal-average intensity	13	3.1	Acoustic pulse waveform
7	7.3.2.4	Derived ultrasonic power (or from IEC 61161)	14	3.16 to 3.19	Location of any of the parameter values
			15	3.54	Pulse duration
			16	3.58	Pulse repetition rate
			17	3.64	Scan repetition rate
			18	3.3	Acoustic-working frequency
			19	3.90	Ultrasonic transducer element group
			20	3.91	Ultrasonic transducer element group dimensions

[a] For this type of application the peak-compressional acoustic pressure is assumed to be of equal magnitude to the peak-rarefactional acoustic pressure.

Subclause 7.2 deals with the determination of some of the primary pressure parameters.

NOTE See Figure 4 for a schematic representation of some of the pulse parameters.



Key

t_a time to reach the 10 % value of $ppsi$

t_b time to reach the 90 % value of $ppsi$

X time

Y pressure

Figure 4 – Schematic diagram of the method of determining pulse duration

7.2 Primary pressure parameters

7.2.1 General

With the **ultrasonic transducer** and **hydrophone** mounted in accordance with 5.2.2, 5.2.3 and 6.2, any of the following acoustic parameters can be determined using the definitions listed in Clause 3.

NOTE When measurements are being made in order to conform with an individual standard (for example IEC 62359 or IEC 61157), the parameters required are those specified in that standard.

In the case of measurements made in a specified plane, the position of the plane from the face of the **ultrasonic transducer** shall be stated and the reported values shall be described as representing that plane only:

– **beamwidth** specified at −6 dB level;
– **beamwidth** specified at −12 dB level;
– **beam area** specified at −20 dB level;
– **beam area** specified at −6 dB level;
– **output beam dimension**;
– **scan-area**;
– location of the **spatial-peak temporal-peak acoustic pressure**;
– location of the maximum of the **pulse-pressure-squared integral**;
– location of the **spatial-peak temporal-average intensity**;
– **ultrasonic scan line separation**;
– **ultrasonic transducer element group dimensions**;

– **pulse repetition rate**;
– **scan repetition rate**;
– **pulse duration**;
– **arithmetic-mean acoustic-working frequency** or **magnitude-weighted acoustic-working frequency**;
– **acoustic pulse waveform**;
– **local distortion parameter**;
– **peak-compressional acoustic pressure**;
– **peak-rarefactional acoustic pressure**;
– **spatial-peak RMS acoustic pressure**.

NOTE **Arithmetic-mean acoustic-working frequency** is equivalent to center frequency in [30].

7.2.2 Peak-compressional acoustic pressure and peak-rarefactional acoustic pressure

A systematic search shall be made to locate the point or points of **peak-compressional acoustic pressure** and **peak-rarefactional acoustic pressure**.

NOTE Particular regions of interest are those areas where on the **beam axis** maxima or minima of any of these pressures occur.

Reporting of **peak compressional acoustic pressure** should be accompanied by a description of any regularization filter used (see 5.1.7.2.3, NOTE 6). At a minimum, that description should specify the −3 dB corner frequency of the regularization filter.

7.2.3 Spatial-peak RMS acoustic pressure

A systematic search shall be made to locate the point of **spatial-peak RMS acoustic pressure**.

NOTE 1 Particular regions of interest are those areas where on the **beam axis** maxima or minima of this pressure occur.

Measurements shall be made over an integral number of **acoustic repetition periods** and shall include all parts of the **acoustic repetition period** when there is ultrasound incident on the **hydrophone**.

In the case of **scanning modes**, in order to determine the **RMS acoustic pressure** over the **scan repetition period**, it is essential to measure the received signal from consecutive **ultrasonic scan lines**. This received signal corresponds to excitations from consecutive **ultrasonic transducer element groups**, in the case of multi-element **ultrasonic transducers**, or from consecutive rotational **ultrasonic scan lines** in the case of sector scanners or phased-array scanners.

For ultrasonic equipment exhibiting short pulse waves, it is more appropriate to determine the **pulse-pressure-squared integral** (see 7.3.2).

NOTE 2 With existing **hydrophones**, it can be essential to rotate the **hydrophone** about its axis, which is perpendicular to the **azimuth plane**, in order to maximize the received signal in each case.

7.2.4 Local distortion parameter

The propagation of ultrasound in water at the acoustic pressures and frequencies frequently encountered in medical ultrasonic fields is not a linear process and the **acoustic pulse waveform** is often distorted as a result. In diffractive fields, enhanced differences exist between the **peak-compressional acoustic pressure** and the **peak-rarefactional acoustic pressure**. To determine the significance of the distortion in the characterization of ultrasonic fields, the degree of nonlinear propagation can be quantified by calculation of the **local distortion parameter**, σ_q (see 3.38), according to IEC TS 61949.

The following regimes can be defined.

a) σ_q < 0,5: little nonlinear distortion has occurred. The amplitude at f_{awf} differs by less than 5 % from the value in the absence of nonlinear effects.

b) 0,5 ≤ σ_q ≤ 1,5: considerable distortion has occurred. A broadband **hydrophone** should be used with a sensitivity that meets the requirements of 5.1.7.1. The amplitude in a one half octave band centred at f_{awf} will differ from its value in the absence of nonlinear effects by between 5 % and 25 %.

c) σ_q > 1,5: considerable nonlinear distortion and also attenuation at f_{awf} has occurred. A broadband **hydrophone** should be used as in b) above. The amplitude in a one half octave band centred at f_{awf} will differ by more than 25 % from the value in the absence of nonlinear effects.

NOTE In b) and c) above, the acoustic pressure spectra $\mathcal{F}(p(t))$ are likely to contain a significant portion in the frequency range of several times the **acoustic-working frequency**, and within waveform deconvolution (see 5.1.7.2) broadband calibration data of the **hydrophone** are needed.

7.3 Intensity parameters derived from acoustic pressure

7.3.1 General

As **hydrophones** measure acoustic pressure, it is appropriate that the specification of quantities based on **hydrophone** measurements be given in terms of acoustic pressure. Hence the parameters given in 7.2 and in Clause 3 shall be the preferred parameters for specification.

Under conditions when it is reasonable to assume plane progressive wave propagation, it is possible to convert the measured **instantaneous acoustic pressure** parameters to true intensity. If this is done, then it shall be clearly stated that the plane progressive wave approximation has been used.

In this case the **instantaneous intensity** is approximated by the **derived instantaneous intensity**, $I(t)$, given by

$$I(t) = p(t)^2 / \rho c \qquad (18)$$

where

ρ is the density of water;

c is the velocity of sound in water (see Annex B).

The following intensity parameters may be determined from the pressure parameters:

– **spatial-peak temporal-peak intensity** $I_{sptp} = (p_{sptp})^2 / \rho c$ (19)

– **spatial-peak temporal-average intensity** $I_{spta} = (p_{spr})^2 / \rho c$ (20)

– **spatial-average pulse-average intensity** I_{sapa}

– **spatial-average temporal-average intensity** I_{sata}

– **time-window-average intensity** $I_{w,\Delta t/s}(t)$.

The procedures used for the determination of the first two parameters shall be similar to those for the equivalent acoustic pressure parameters. However, in this case the parameter recorded at each point in the acoustic field shall be the square of the **instantaneous acoustic pressure**.

NOTE If the **local distortion parameter** exceeds 0,5, then the conversions of measured pressure parameters to intensities might not be valid or sufficiently accurate [31].

7.3.2 Intensity parameters using pulse-pressure-squared integral

7.3.2.1 Pulse duration

The **pulse duration** is equal to 1,25 times the 10 % to 90 % rise time of the time integral of the square of the **instantaneous acoustic pressure**. The points of time, t_a and t_b, at which this time integral is 10 % and 90 % of the **pulse-pressure-squared integral**, respectively, follow from Formula (21) and Formula (22).

$$\frac{1}{M^2}\int_{t_1=0}^{t_a} u^2(t)\,\mathrm{d}t = 0{,}1\,ppsi \qquad (21)$$

$$\frac{1}{M^2}\int_{t_1=0}^{t_b} u^2(t)\,\mathrm{d}t = 0{,}9\,ppsi \qquad (22)$$

where

M is the general term of the **hydrophone** sensitivity;

$u(t)$ is the measured output voltage of the **hydrophone**.

The **pulse duration** shall then be calculated as

$$t_d = 1{,}25(t_b - t_a). \qquad (23)$$

7.3.2.2 Spatial-peak pulse-average intensity

Spatial-peak pulse-average intensity shall be calculated with the maximum value of the **pulse-pressure-squared integral** as measured on the **beam axis**, using:

$$I_{sppa} = \frac{1}{t_d \rho c}\,ppsi \qquad (24)$$

where

ρ is the density of water;

c is the velocity of sound in water (see Annex B);

ρc is the characteristic acoustic impedance of pure water (= 1,48 × 10^6 kg m^{-2} s^{-1} at 20 °C);

t_d is the **pulse duration**.

7.3.2.3 Spatial-peak temporal-average intensity

For the **non-scanning mode** the **spatial-peak temporal-average intensity** is calculated with the maximum value of the **pulse-pressure-squared integral** value in a single beam, using:

$$I_{\text{spta}} = \frac{prr}{\rho c} \max_z \left[ppsi(z) \right] \tag{25}$$

where

prr is the maximum **pulse repetition rate** of the **non-scanning mode**.

For a **scanning mode** (e.g. automatic B-mode) the I_{spta} value shall be measured including the contribution of overlapping **ultrasonic scan lines**. It means that more **pulse-pressure-squared integral**(s) are processed, indicated by the sum of **pulse-pressure-squared integral**(s):

$$Sppsi = ... + n_{\text{pps,c-2}}\, ppsi_{\text{c-2}} + n_{\text{pps,c-1}}\, ppsi_{\text{c-1}} + n_{\text{pps,c}}\, ppsi_{\text{c}} + n_{\text{pps,c+1}}\, ppsi_{\text{c+1}} + n_{\text{pps,c+2}}\, ppsi_{\text{c+2}} \cdots \tag{26}$$

where

$ppsi_{\text{c}}$	is the **pulse-pressure-squared integral** belonging to the central scan line;
$ppsi_{\text{c+1}}$, $ppsi_{\text{c−1}}$, etc.,	are the **pulse-pressure-squared integrals** of diminishing values of the successive adjacent **ultrasonic scan lines**;
$n_{\text{pps,c+1}}$, $n_{\text{pps,c−1}}$, etc.,	represent the number of repeating pulses per **ultrasonic scan line**.

From the **scan repetition rate** and the number of **ultrasonic scan lines**, the **ultrasonic scan line separation** at the depth where the maximum I_{spta} will be found is calculated. Alternatively, the **ultrasonic scan line separation** may be found by scanning the **hydrophone** in the scan direction and measuring the distances between the maxima found in the scan.

Using this **ultrasonic scan line separation**, the contribution of adjacent **ultrasonic scan lines** can be calculated from the results of a lateral line scan in the **scan plane**. In the summation of the $ppsi$ values, all contributing **ultrasonic scan lines** are to be included over a period of time sufficiently long to include all significant acoustic information.

The **spatial-peak temporal-average intensity** for the **scanning mode** then results in

$$I_{\text{spta}} = \frac{srr}{\rho c} \max_z \left[Sppsi(z) \right] \tag{27}$$

where

srr is the maximum **scan repetition rate** of the **scanning mode**.

7.3.2.4 Derived ultrasonic power

If the determination of total ultrasonic power P of a single, stationary, beam is done by means of planar scanning, then it shall be performed with a calibrated **hydrophone** in accordance with IEC 62127-2, based on Formula (28):

$$P = \iint_{s} I_{\text{ta}}(x,y)\,\mathrm{d}x\mathrm{d}y \tag{28}$$

where

$I_{\text{ta}}(x,y)$ is the **temporal average intensity** at the point defined by the orthogonal coordinates x and y.

The energy E of the beam is calculated as the summation of all contributions of the $ppsi(x,y)$ at all points in a scanned area:

$$E = \frac{dS}{\rho c}\sum_{i} ppsi(x_i, y_i) \tag{29}$$

where

dS is the step area, i.e. the product of distance dx and dy between two successive measuring points (samples) in the scanned area, assuming that dx and dy are both constant throughout the scan and that the scan has a rectangular geometry.

The total ultrasonic power then follows from

$$P = E\,prr \tag{30}$$

The total ultrasonic power may also be calculated from

$$P = \frac{dS}{\rho c}\sum_{i} p_{\text{RMS}}^{2}(x_i, y_i) \tag{31}$$

In the **scanning mode**, the total ultrasonic power for each mode of operation may be calculated from

$$P = E\,srr\,m\,n_{\text{pps}} \tag{32}$$

where

E is the energy of the beam, as used before;

m is the number of **ultrasonic scan lines** per image for spatial distribution;

n_{pps} is the **number of pulses per ultrasonic scan line**.

The total ultrasonic power during the **scanning mode** will be the sum of all ultrasonic powers during the acting operation modes.

NOTE 1 The method is specifically useful in circumstances where a sensitive enough radiation force balance is not available or where the physical dimensions or **acoustic-working frequency** of the ultrasound transducer do not allow using a radiation force balance. Usually, the measurement of **total ultrasound power** is more accurate to be measured by means of the radiation force method (see IEC 61161).

NOTE 2 Formula (30) applies to **scanning modes** or **non-scanning modes** only if E is the same for each pulse.

NOTE 3 Formula (32) assumes the same **number of pulses per ultrasonic scan line** n_{pps} for the specific **scanning mode**.

NOTE 4 Formula (32) assumes that the acoustic power of each pulse in each of the m **ultrasonic scan lines** is the same. This is not true if different scan lines use different pulse types or aperture sizes.

8 Requirements for specific ultrasonic fields

8.1 General

The requirements listed in Clause 8 are either an addition to or supersede the applicable ones specified in Clause 5. See also Annex H. For the determination of absolute values of acoustic pressure or derived intensity (see 3.14), the **hydrophone** shall be calibrated in accordance with IEC 62127-2.

8.2 Diagnostic fields

8.2.1 Simplified procedures and guidelines

The measurement of the **pulse-pressure-squared integral** is required for many aspects of ultrasonic field characterization.

In cases where the **acoustic pulse waveform** does not change shape within any particular measurement plane perpendicular to the **beam axis**, the **peak acoustic pressure** may be used instead of the **pulse-pressure-squared integral**.

NOTE 1 Frequently, this situation is encountered in continuous wave ultrasonic fields such as continuous wave Doppler and physiotherapy transducers.

If all the acoustic scan lines are assumed to be of equal magnitude and beam shape, the overlapping scan line contribution may be determined knowing the beam shape and the separation between scan lines in the measurement plane.

All acoustic scan lines should be sampled in order to locate the one with the largest **peak acoustic pressure**.

NOTE 2 In practice, the variation between the acoustic output of different scan lines will depend on the type of scanner. For sector scanners using rotating single-element transducers with a constant acoustic coupling path, the difference would be expected to be small. In this case, sampling the **central scan line** and the two extreme scan lines at the edge of the sector would be undertaken and an assessment made on whether it is necessary to determine the output of other scan lines. If the difference between the **peak acoustic pressures** is less than 10 %, it is unlikely that other scan lines need to be measured other lines.

8.2.2 Pulsed wave diagnostic equipment

8.2.2.1 Diagnostic fields in general

A **hydrophone** with an active element of diameter of approximately 0,5 mm or less shall be used. However, in addition the recommendations of 5.1.6.1 and 5.1.6.2 should be followed.

The repeatability of the positioning systems shall be ±0,01 mm for three orthogonal adjustments for the **hydrophone** (or transducer if the latter is the item that is scanned).

For waveforms that are distorted by nonlinear propagation effects, i.e. those with a **local distortion parameter** σ_q (see 3.38) greater than 0,5, either a **hydrophone** with adequate **bandwidth** (see 5.1.7) shall be chosen, or voltage-to-pressure conversion shall be performed using deconvolution of the frequency response of the **hydrophone** (see 5.1.7.2 and Annex D).

Ceramic needle type **hydrophones** are not recommended (see Clause B.9).

NOTE 1 In practice, the accuracy and repeatability of positioning systems is most important in the direction perpendicular to the propagation direction and, in most cases, ±0,05 mm is often adequate. In the propagation direction, an accuracy of ±0,1 mm is often adequate for most measurement situations. The highest accuracy would be required for highly focused fields (wide aperture) and at high frequencies (see 5.2.2.3).

NOTE 2 In case of distorted waveforms, additional demands are placed on the angular alignment because of the dependence of the directional response on frequency. Under these conditions, it is important to optimize the rotation of the **hydrophone** to ensure the maximum received signal (see 5.2.2).

NOTE 3 At typical focal distances, the square law relationship between acoustic pressure and intensity is usually assumed in order to derive intensity parameters. This assumption is made despite the **uncertainty** associated with the nonlinear distortion that can take place.

8.2.2.2 Diagnostic fields in the absence of scan-frame synchronization

The ultrasound fields generated by clinical imaging scanners have become increasingly complex as technology has advanced. The parameters defined in Clause 3 to describe the spatial and temporal variation of pressure and intensity in the ultrasound field work well for unscanned fields such as those used for pulsed Doppler or M-mode. However, it is becoming increasingly difficult to use all of these definitions for the complicated pulse sequences generated in scanned modes such as colour-flow imaging. In some cases, it might not be possible to determine an **acoustic repetition period** for these sequences.

A modified set of acoustic parameters that might be more appropriate to modern imaging equipment is outlined in Annex F.

8.2.3 Continuous wave diagnostic equipment

A **hydrophone** with an active element of diameter approximately 0,5 mm or less shall be used. However, in addition the recommendations of 5.1.6.1 and 5.1.6.2 should be followed.

The repeatability of the positioning systems shall be ±0,01 mm for three orthogonal adjustments for the **hydrophone** (or transducer if the latter is the item that is scanned).

For waveforms that are not distorted by nonlinear propagation effects, i.e. those where the **local distortion parameter** σ_q (see 3.38) is smaller than 0,5, it is not necessary to use a broadband **hydrophone** (see 5.1.7).

In ultrasonic fields where the **peak acoustic pressure** occurs close to the face, e.g. at distances less than the minimum **output beam dimension**, the approximation for ultrasonic intensity (see 7.3) may be made, provided that an appropriate **uncertainty** is taken into account.

PVDF or ceramic needle devices (see Clause B.9) are satisfactory for measurements on continuous wave Doppler transducers. Membrane **hydrophones** may be used providing care is taken to ensure the reflection from the membrane does not interfere with the output from the **ultrasonic transducer** (see 5.2.2.2).

8.2.4 Diagnostic equipment with low acoustic output

For **hydrophone** measurements on diagnostic systems that fulfil the criteria of IEC 60601-2-37:2007, 201.12.4.2 a) and b) to be exempt from the requirement to display thermal and mechanical indices, the narrowband approximation can be applied even if the criteria of 5.1.7.1 cannot be fulfilled. When using this simplification, the additional measurement **uncertainty** reflecting the limitations of a narrowband measurement of a broadband signal shall be considered, in particular, when comparing output data against thresholds.

8.3 Therapy fields

8.3.1 Physiotherapy equipment

Methods and requirements listed in IEC 61689 or IEC 63009 shall be followed depending on the **acoustic-working frequency** of the equipment.

For waveforms that are not distorted by nonlinear propagation effects, i.e. those where the **local distortion parameter** σ_q (see 3.38) is smaller than 0,5, it is not necessary to use a broadband **hydrophone**.

If an absolute value of acoustic pressure or derived intensity (see 3.14) is needed, the **hydrophone** shall be calibrated in accordance with IEC 62127-2 at the f_{awf}. For **acoustic-working frequencies** f_{awf} below 0,5 MHz, calibration shall be in accordance with IEC 60565-1.

For fields generated by ultrasound physiotherapy devices a linear response, as referred to in 5.1.8, up to 1 MPa is generally adequate.

Measurements of effective radiating area (see for definition: IEC 61689) shall use a needle **hydrophone**, with the active element made from either polyvinylidene fluoride (PVDF) or piezoceramic. Care should be taken to ensure reflections from the needle and its support do not interfere with the measurements.

Cavitation effects can cause damage to **hydrophones** at the pressures that can be produced by physiotherapy transducers. It is, therefore, essential to use degassed water for measurements with **peak acoustic pressure** above 0,3 MPa.

The maximum **effective hydrophone size** used for the measurements shall be a_{max} so that:

$$a_{max} \leq \lambda/2,5 \tag{33}$$

NOTE 1 In most cases, in physiotherapy, the above criterion represents an **effective hydrophone size** larger than that recommended in 5.1.6. It has been derived from an analysis of its effect on the effective radiating area, rather than on peak pressures, and the former is less sensitive to the effects of spatial averaging.

NOTE 2 **Hydrophones** are also used to measure the beam non-uniformity ratio and the above criterion is also acceptable for those measurements [32], [33].

NOTE 3 For some **treatment heads**, ultrasound reflected back to the **treatment head** can affect output power, particularly in the case of coherent reflections from absorbers with planar smooth surfaces. In these instances, an improved approximation to free field conditions can be obtained by using acoustic absorbers with textured surfaces.

8.3.2 High intensity therapeutic ultrasonic fields

To support acoustic output characterization in accordance with IEC 60601-2-62, specific requirements on the measurement of fields generated by high intensity focused ultrasound (HIFU) and high intensity therapeutic ultrasound (HITU) are specified in IEC TS 62556 with respect to measurement at relatively low output levels and methodology for extrapolating these to higher therapeutic level fields.

For measurements at focus at clinical driving levels, the upper frequency range limit of 8 f_{awf} in the narrow-band approximation requirement according to Formulas (14) and (15) (see 5.1.7.1) shall be replaced by min [20 f_{awf}, 100 MHz], and the −3 dB cut-off frequency of the low-pass filtering within deconvolution regularization (see 5.1.7.2.3) shall be at minimum the lesser of 20 times the **acoustic-working frequency** f_{awf} or 100 MHz. Extrapolation ranges for **hydrophone** calibration data $\underline{M}_L(f)$ shall be limited to below half of the **acoustic-working frequency** towards zero and above the lesser of 20 times the **acoustic-working frequency** or 100 MHz towards the Nyquist frequency, e.g. for $0 \le f < f_{awf}/2$ and for min [20 f_{awf}, 100 MHz] $< f \le f_{Nyquist}$.

NOTE 1 More restrictive **bandwidth** criteria than in general are needed here for adequate waveform reproduction due to the large number of harmonics.

NOTE 2 **Hydrophone** calibration data are expected to be available up to 100 MHz and **acoustic-working frequencies** are usually below 5 MHz for high intensity ultrasonic fields.

A linear amplitude response as specified in 5.1.8 to extend up to 5 MPa may not be sufficient in many measurement situations for HIFU or HITU. If pressure signals exceed the linear amplitude range of the **hydrophone** as defined in IEC 62127-3, corrections shall be employed to compensate for the amplitude distortion within the 10 % criterion of IEC 62127-3 caused by the nonlinearity in the pressure response of the **hydrophone.** The correction shall be taken into account in determining acoustic quantities and associated **uncertainties.** If no such corrections can be implemented, or if the pressure range exceeds the damage threshold of the **hydrophone**, the **hydrophone** shall not be used.

NOTE 3 Extended linearity is needed here due to the large **peak compressional acoustic pressures** in high intensity ultrasonic fields.

NOTE 4 The maximum pressure at the surface of a **hydrophone** can be significantly higher than the measured free-field pressure due to the acoustic reflection of the incident wave. This needs to be taken into account within guidelines for **hydrophone** usage and for corrections for non-linear effects.

8.3.3 Non-focused and weakly focused pressure pulses

Specific comments on the measurement of fields generated by non-focusing pressure pulse sources for pain treatment and other applications are specified in IEC 63045.

NOTE Such pressure pulse fields are usually described using pressure parameters rather than derived intensity parameters.

8.4 Surgical fields

8.4.1 Lithotripters and pressure pulse sources for other therapeutic purposes

Specific requirements for the measurement of fields generated by pressure pulse lithotripters are specified in IEC 61846.

For fields generated by lithotripters, the linear response, as referred to in 5.1.8, should be known at least up to 80 MPa and in cases where measurements indicate higher **peak compressional pressure** values up to 150 MPa. Any nonlinearity in the pressure response of the **hydrophone** shall be taken into account in determining acoustic quantities and associated **uncertainties**.

NOTE 1 Pressure pulses are not only used for lithotripsy, but also for the treatment of pain, for example shoulder calcification pain, tennis elbow, heel spur pain, etc. as well as for other medical applications (cardiac shockwave application).

NOTE 2 Such pressure pulse fields are usually described using pressure parameters rather than derived intensity parameters.

8.4.2 Low frequency surgical applications

For the characterization of low frequency surgical systems using a **hydrophone**, the **hydrophone** shall be calibrated in accordance with IEC 60565-1.

Requirements as listed in Clause 5, Clause 6 and Clause 7 do not apply to this type of equipment.

Specific requirements for the measurement of fields generated by low frequency surgical systems are specified in IEC 61847.

8.5 Fields from other medical applications

Presently there are no specific requirements for this type of equipment.

9 Conformity statement

9.1 General

The acoustical parameters shall be chosen from those defined in this document. To ensure traceability, the settings should be recorded of any controls on the equipment console which might affect the field generated.

For conformity with this document, the following shall be stated for any parameter that is reported:

a) the arithmetic mean determined from measurements on a group of n nominally identical systems, each with the acoustic output settings yielding the maximum output, where $n \geq 3$; and

b) the overall **uncertainty** of the value determined under a).

   This overall **uncertainty** shall be calculated using an appropriate measure (with 95 % confidence, for 95 % of the population) of the statistical variation and the measurement **uncertainty** (at a level of confidence of 95 %).

   The tolerance interval is to be understood in accordance with ISO 16269-6. More guidance on assessment of **uncertainties** is given in Annex I.

   Measurement **uncertainty** involves many components (see Annex I). It shall be an assessment of the contributions of all **uncertainties** (these referring to measurements made on one system). The measurement **uncertainty** shall be calculated as expanded **uncertainty** corresponding to a level of confidence of 95 %. The method of combining the **uncertainty** contributions specified by ISO/IEC Guide 98-3:2008 shall be followed.

NOTE "tolerance interval" refers to the production scatter and "**uncertainty**" refers to the measurement method.

9.2 Maximum probable values

A requirement of the type "shall conform to" means that the measurement **uncertainty** and tolerance interval shall be included when comparing against a limit. The maximum probable values shall be determined in accordance with the following procedure:

a) measurements shall be carried out on a group of n nominally identical systems, each with the acoustic output settings yielding the maximum output, where $n \geq 3$;

b) the maximum probable value shall be calculated by linear summation of the upper tolerance limit of the one-sided tolerance interval (with 95 % confidence, for 95 % of the population) and the measurement **uncertainty** (at a level of confidence of 95 %).

The tolerance interval is to be understood in accordance with ISO 16269-6. More guidance on assessment of **uncertainties** is given in Annex I.

NOTE 1 "tolerance interval" refers to the production scatter and "**uncertainty**" to the measurement method.

It may not be possible to comply with all the requirements of this document. If measurements are made for the purposes of acoustic output specification and labelling which do not comply with a particular requirement then the lack of conformity shall be clearly stated when reporting results. A statement of non-conformity shall include the relevant clause or subclause and shall give the reason for non-conformity.

NOTE 2 Selected examples of non-conformity are as follows, where IEC 62127-1 refers to this document.

a) IEC 62127-1 was complied with, except for 5.1.7; the sensitivity of the **hydrophone** at 20 MHz was 60 % below the sensitivity at 5 MHz.

b) IEC 62127-1 was complied with, except for 5.1.9; the change in amplifier gain from 5 MHz to 20 MHz was −5 dB.

c) IEC 62127-1 was complied with, except for 5.1.6; the **effective hydrophone size** was 0,5 mm.

9.3 Sampling

For good manufacturing practice, measurements should be taken on a certain percentage of production but, exceptionally, could be taken on each manufactured unit.

For the purpose of determining the product variation of the reported parameters when full repeat measurements of all parameters are impractical, this variation may be estimated from partial repeat measurements (by repeating the measurement of a subset of the parameters).

Standard statistics on probability and confidence as given in ISO 16269-6 shall apply.

Annex A
(informative)

General rationale

This Annex A provides a concise rationale for the important requirements of this document and is intended to provide background information for those who are familiar with the subject of this document but who have not participated in its development. An understanding of the reasons for the main requirements is considered to be essential for the proper application of this document. Furthermore, as medical ultrasonic equipment continues to develop, it is believed that a rationale for the present requirements will facilitate the application of this document to new equipment and facilitate any future revision of to this document.

The numbering in this Annex A refers directly to this document.

Clause 3: Many of the acoustic parameters are defined such that either a single value may be given or, alternatively, a value may be given that corresponds to measurements in a specified plane. This option permits greater flexibility in the application of this document. For instance, in the case of transducers used for physiotherapy, or divergent beam transducers such as used for foetal monitoring, it may not be appropriate to determine acoustic parameters in the plane containing the maximum **spatial-peak temporal-peak acoustic pressure**. The form of definitions used in this document permits a choice of measurement plane based on criteria other than those given in this document.

Terms 3.25 and 3.27: Both the sensitivity of a **hydrophone** when connected to an electrical load, such as an oscilloscope, and the sensitivity into an infinite impedance load (open circuit) are defined as they are both relevant to the practical application of **hydrophones**.

Term 3.38: At the high acoustic pressures generated by medical ultrasonic diagnostic equipment (**peak-compressional acoustic pressures** in the range of 0,1 MPa to 10 MPa), there can be severe distortion of the **acoustic pulse waveform**, especially in the focal region. An important aspect of this document is that it addresses these nonlinear effects that are associated with the propagation of ultrasound in water. This distortion is caused by the fact that, during an acoustic cycle, the compressional part of the wave travels faster than the rarefaction part giving rise to a progressive distortion of the waveform. In general, the degree of distortion present at any point in an acoustic field increases with the increase in a number of factors. These are the distance from the transducer, the **acoustic frequency**, the **peak acoustic pressure** at the face of the **ultrasonic transducer**, the nonlinearity parameter for the propagating medium (water) and the degree of focusing. While it is accepted that absorption and scattering of ultrasound in various types of tissue will lead to a reduction in the **peak acoustic pressure** in many medical imaging situations, for certain applications this reduction will not be significant. For instance, imaging through the eye, bladder and amniotic fluid are specific examples where much of the path is through liquid. To cope with this nonlinearity, this document includes, in the list of parameters that may be used for specification purposes (see 7.2.1), the parameter related to nonlinearity. It is the **local distortion parameter** that is an index predicting the importance of nonlinear distortion at the focus, see IEC TS 61949. From this parameter, the bandwidth of the **hydrophone/amplifier** and the need for corrections to measured peak pressures may be determined.

Terms 3.50 and 3.51: Again, both the **peak acoustic pressures** are defined as often there is a difference of up to a factor of three between them. As the **peak-rarefactional acoustic pressure** is most likely to be relevant to acoustic cavitation (the decompression part of the cycle), it is important to distinguish between them.

Term 3.87: The definition is intended to distinguish between the **ultrasonic scan lines** that intersect the chosen plane at gradually changing positions during the acoustic scan, and those that essentially do not. For instance, those in the latter category would be multiple excitations of the same **ultrasonic transducer** or **ultrasonic transducer element group** for focusing at different depths or for interlaced Doppler lines in duplex scanners.

Subclause 5.1.7: Broad **hydrophone bandwidths** are important for characterizing the temporal characteristics of medical ultrasound fields when short pulses are used or when significant nonlinear distortion is present. One consequence of nonlinear distortion is that an increased high-frequency response is necessary due to the higher harmonics generated [9]. In [9] it was found that a ±3 dB **bandwidth** of at least eight times the **acoustic-working frequency**, f_{awf}, was reasonable for keeping measurement errors below about 5 %. A lower limit of the frequency band used in the determination of the **hydrophone bandwidth** well below f_{awf} is desirable also, particularly for accurate measurement of the **peak-rarefactional acoustic pressure**, p_r [10]. One reason for increased low-frequency **hydrophone** response is that the shorter the pulse, the broader is the spectrum below as well as above the centre frequency. Additionally, for p_r, the waveform asymmetry resulting from the combined effects of source diffraction and nonlinear propagation causes the portion of the pulsed waveform where p_r occurs to be dominated by low-frequency components. In [10], which contains both simulations and measurements of the effects of band-limited response on short pulses, based on the **hydrophone assembly** having a single-pole, high-pass response, it was found that to reduce measurement errors to less than 5 % to 10 %, the **hydrophone assembly** lower limit of the frequency band used in the determination of the **hydrophone bandwidth** should extend to at least an order of magnitude below f_{awf}. Thus, in this document it is recommended that, if possible, the lower and upper limits for the combined frequency response of all components used to condition, amplify, or record the pulsed waveforms be set at $f_{awf}/16$ and 8 f_{awf}. For practical reasons, the lower and upper limits of the frequency band used in the determination of the **hydrophone bandwidth** are $f_{awf}/2$ and 8 f_{awf}. For the frequency ranges below $f_{awf}/2$ and above the lesser of 4 f_{awf} and 100 MHz, however, the **hydrophone** calibration data may be extrapolated if they are not available from calibration measurements (see Annex D). If narrow-band requirements are not fulfilled, broadband measurements using waveform deconvolution are performed in accordance with 5.1.7.2 and similar **bandwidth** criteria have been adopted for this method.

NOTE 1 An absolute upper limit of 40 MHz was specified in IEC 62127-1:2007 due to the limitation of the accompanying **hydrophone** calibration standard IEC 62127-2:2007. However, since then calibration methods have been extended [11], [18], [34], [35], [36], [37], [38] and this limitation has been dispensed with.

NOTE 2 The upper extrapolation frequency limit of 4 f_{awf} or 100 MHz rather than 8 f_{awf} is allowed to achieve practicability in particular for f_{awf} > 12 MHz and for f_{awf} > 25 MHz, respectively.

NOTE 3 More restrictive **bandwidth** criteria are required in 8.3.2 for high intensity therapeutic ultrasonic fields.

Clause 7: A large number of acoustical parameters are defined in Clause 3 and given here. These provide the basis for the specification of a wide range of ultrasonic fields, although emphasis has been given to medical ultrasonic equipment. However, for any particular equipment, it is expected that only a small group of these acoustical parameters will be chosen, for instance, for the purpose of acoustic output labelling.

Clause 9: It is not the purpose of this document to specify the acoustical parameters for acoustic output labelling. Clause 9, however, provides the necessary guidelines for the declaration of acoustical parameters for the purpose of acoustic output labelling. Provision is made for the reporting of results when the measurement procedures do not meet all the requirements of this document.

A general discussion on the accuracy of the measurement of acoustic quantities is given in Annex I.

Annex B
(informative)

Hydrophones and positioning

B.1 General

There are four basic types of **hydrophone** currently in use. Two **hydrophone** constructions employ an active element made from either a piezoelectric ceramic or polymer (usually polyvinylidene fluoride, PVDF), which is supported at the end of a needle-like structure. The third type is the membrane **hydrophone**, which uses a large sheet of PVDF, the central region of which is piezoelectrically activated. The fourth type is the fibre-optic **hydrophone**. Refer to Clause B.9 for a more detailed assessment of the four types of **hydrophone**.

None of these current designs of **hydrophone** yields devices that meet all the requirements of this document over the full frequency range of ultrasonic applications. Preliminary reports concerned with the performance of optic and fibre-optic **hydrophones** indicate that in the future they could meet these requirements and eliminate the need for spatial averaging corrections (see [39], [36], [40]). Nevertheless, the relative importance of the requirements depends on the particular ultrasonic field to be characterized. For instance, in the **far field** of a plane piston **ultrasonic transducer**, the size of the active element can be up to two or three times the acoustic wavelength. Also, for acoustic pressures less than 0,1 MPa, the **bandwidth** of the **hydrophone** is less critical because nonlinear distortion is unlikely to be significant at the propagation distances normally encountered. Likewise, for measurements on pulsed fields, reflections from membrane **hydrophones** are less important than for continuous wave fields.

B.2 Electrical loading considerations

The **end-of-cable loaded sensitivity** of a **hydrophone**, (see 5.1.3), should be determined from its **end-of-cable open-circuit sensitivity** using the method described in IEC 62127-2. Also, in IEC 62127-2 the effects of changing the loading conditions are described.

B.3 Hydrophone signal amplifier

The purpose of a **hydrophone** signal amplifier is to provide a buffer between the **hydrophone** and the measurement system. Such a buffer overcomes cable resonance effects at high frequencies and provides extra gain and a constant electrical load for the **hydrophone**. An amplifier may be incorporated in the **hydrophone** as an integral amplifier, in which case it is not possible to separate the two devices. Alternatively, it may be a separate device into which the **hydrophone** is plugged either directly or using the connector at the end of the **hydrophone** cable. Disadvantages of any **hydrophone** amplifiers are that they tend to limit dynamic range and will need a power supply, thereby adding complexity. An additional disadvantage of an integral amplifier can be the need for extra power supply wires at the **hydrophone**. See also [23].

B.4 Hydrophone cable length and amplifiers

When a **hydrophone** is connected to a voltage measuring device such as an oscilloscope, or to an amplifier, it is important to consider the electrical characteristics of the resulting measurement systems.

It is not usually possible for the electrical output impedance of a **hydrophone**, excluding any integral cable, to be matched to the impedance of the cable. This is because the output impedance of a **hydrophone** usually exceeds that of the cable. Consequently, it is not practical to use an electrical load at the end of the cable that matches the cable impedance if a significant loss of signal amplitude and waveform quality is to be avoided. Hence, without an electrically matched cable and load, reflections of the signal will occur at the end of the cable, causing "ringing". These cable resonances will be maximum when the cable length equals one quarter of the wavelength of the electrical propagation in the cable. Typically, for normal coaxial cables, the resonance occurs at cable lengths (in metres) given by 50/$\{f\}$ where $\{f\}$ denotes the numerical value of the frequency in MHz. Thus, at 50 MHz, a cable length of 1 m will cause resonances. The significance of resonances will depend on the mismatch of the electrical impedances at the cable/load and cable/**hydrophone** interfaces. In addition, it would be dependent on the frequency content of the **hydrophone** signal, which depends on the **bandwidth** of the **hydrophone** (excluding any integral cable). Providing the thickness resonance mode of the **hydrophone** occurs at a frequency below that of the cable resonance, the effects of cable resonance will probably be negligible.

Hence, if cable resonances occur at frequencies within the range of lower and upper limit of the frequency band used in the determination of the **bandwidth** of the **hydrophone**, the cable length should be minimized, and an amplifier placed close to the **hydrophone**. To overcome cable resonances at the output of the amplifier, such an amplifier should have an output impedance matched to any connecting cable, the cable being terminated by a load equal to the characteristic impedance of the cable. Choice of the gain and **bandwidth** of the amplifier is important in order to avoid exceeding its dynamic range. For a **hydrophone** with a sensitivity of 0,03 µV/Pa (typical 0,5 mm PVDF device) applied to measurements of diagnostic ultrasonic equipment where **peak acoustic pressures** can be as high as 10 MPa, an amplifier of unity gain with a dynamic range of 0,6 V peak-to-peak will be needed. See also [23].

Another important aspect in choosing an amplifier is to match the frequency response of the amplifier to that of the **hydrophone**. In particular, to avoid resonance problems, the −3 dB **bandwidth** of the amplifier should not exceed the frequency corresponding to the thickness resonance mode of the **hydrophone**. It is also important to ensure that, beyond the frequency corresponding to the thickness resonance mode of the **hydrophone**, the frequency response of the amplifier decreases at a rate of typically −6 dB per octave.

B.5 Transducer positioning

The following degrees of freedom should be provided for the **ultrasonic transducer**:

Rotational adjustment about three orthogonal axes, one of which should be approximately parallel to the **beam axis**.

Although continuously variable translational degrees of freedom are not essential, it may be necessary to provide some movement in order to position the **ultrasonic transducer** at different places in the tank.

The **ultrasonic transducer** is set up in the coordinate positioning system such that the axis of symmetry of its active element is parallel to the z axis of the **hydrophone** positioning system. Here, the axis of symmetry for **ultrasonic transducers** with cylindrical active elements should be the axis of the cylinder. For **ultrasonic transducers** with spherical active elements, the axis of symmetry should be the axis that passes through the geometrical centre of the sphere and approximately bisects the usable external surface of the **ultrasonic transducer**.

The **ultrasonic transducer** should be mounted in such a way that rotation about the axis of symmetry through 360° is provided.

NOTE For spherical **ultrasonic transducers** consisting of a segment of a sphere, the axis of symmetry would be the axis passing through the geometrical centre of the sphere and through the centre of the circle defining the segment. For some spherical **ultrasonic transducers** consisting of a full (or nearly full) sphere supported by a thin structure such as a tube or rod, the axis of symmetry would be the axis passing through the centre of the sphere and also through the centre of the supported area.

B.6 Alignment of hydrophones

This Clause B.6 provides useful procedures for the alignment of **hydrophones** at the point of **spatial-peak temporal-peak acoustic pressure** in a plane perpendicular to the **beam-alignment axis**.

In the case of membrane **hydrophones**, it is possible to test for correct alignment by rotating the **hydrophone** through 180° about an axis passing through the plane of the active element and noting the change in the received signal when monitoring a pulsed acoustic field. A change in the time delay between excitation and reception indicates a misalignment in the direction normal to the active element, and a change in the amplitude indicates a misalignment in the plane of the active element. In the case of continuous wave excited **ultrasonic transducers**, the same procedure can be used with respect to amplitude, and, if the **hydrophone** has already been aligned to within one quarter of an acoustic wavelength in water, fine adjustments can be made by noting the phase change on rotation.

In the case of needle **hydrophones**, it is possible to test for correct alignment by rotating the **hydrophone** through an angle less than 180° about an axis passing through the plane of the active element.

For both types of **hydrophones**, optical techniques using either a travelling microscope or a small diameter laser beam can be used. Again, the procedure would be to observe the position of the active element and its change when the **hydrophone** is rotated using the micropositioning system.

NOTE To avoid effects on the measurements made on continuous wave fields due to reflection of ultrasound from the surface of membrane **hydrophones**, the **hydrophone** can be tilted. Tilting ensures that the reflected ultrasound either does not interfere significantly with the transducer or is not subsequently reflected from the transducer face, producing interference effects. Two methods can be used to determine the rotation required and a correction applied to measurements for the reduction of the signal due to the directional response of the **hydrophone**.

The first method is to observe the signal from the **hydrophone** and to determine when the interference effects decrease to a negligible level when the **hydrophone** is rotated. To observe the interference effects, the **hydrophone**/transducer separation is altered by about ±0,5 mm, which will cause oscillations of the measured signal if such effects are present. The amplitude of oscillation will decrease as the angle of rotation of the **hydrophone** is increased. Usually, the angle found using this method is less than that determined using the second method, which is to determine the angle at which most of the ultrasound reflected from the membrane will miss the transducer. This angle is determined from tan $(a/2l)$ where a is the geometrical radius of the transducer active element and l is the distance between the transducer face and the **hydrophone**. As an example, consider measurements made using a 0,5 mm bilaminar construction membrane **hydrophone** (thickness 0,05 mm) on a 1,5 MHz physiotherapy transducer with an active element of a diameter of 20 mm. An angular rotation of 14° is needed for measurements made at a distance of 20 mm. Correction to measurements for loss in signal due to the directional response is determined from the measurements of the directional response (see 5.1.4). For the case considered here, a correction of +6 % for acoustic pressure parameters and +12 % for derived intensity parameters is therefore needed.

B.7 Water bath lining material

Conformity with 5.2.3.2 for overall echo reduction of an acoustic absorber can be checked using the procedures described in IEC TS 63081. Echo reduction should be measured at the **acoustic-working frequency** using tone-burst **ultrasound**.

B.8 Recommendations for ultrasonic equipment being characterized

To trigger the measurement system, an electrical signal should be provided synchronized to the excitation of the **ultrasonic transducer** or each **ultrasonic transducer element group**.

For automatic scanning systems, an additional trigger signal should be provided synchronized to each **acoustic repetition period**. These trigger signals should be used to permit the observation of the received signal at the **hydrophone** from any chosen **ultrasonic scan line**.

Alternatively, if the scanning in automatic scanning systems can be "frozen", a trigger signal for the chosen **ultrasonic scan line** should be provided. However, in this case, tests shall be undertaken to ensure that there is no significant variation between a "frozen" beam and a scanning beam. This exercise is not trivial and depends on the type of scanning system. Also, true determination of temporal average parameters is not possible for a "frozen" beam.

NOTE For the separation of interlaced Doppler and scan lines in certain types of duplex automatic scanning systems, it is useful to display the trigger signals on a separate oscilloscope that has a delayed time base and delayed time base output facility. This output can be used to trigger the measurement system.

B.9 Types of hydrophones

B.9.1 Ceramic needle hydrophones

Ceramic needle **hydrophones** usually consist of a small circular disc of piezoelectric ceramic mounted on the end of a needle or pencil-like support. The active element of the **hydrophone** is backed by an acoustically absorbing material and has a size close to the diameter of the support, often in the range of 0,5 mm to 1,5 mm diameter. The signal cable inevitably passes through the ultrasonic field, which can cause problems from the triboelectric effect.

The **end-of-cable open-circuit sensitivity** of these devices is typically 0,7 µV/Pa for a ceramic needle **hydrophone** with an active element of 1 mm diameter. When carefully designed, they may have a relatively flat frequency response to about 6 MHz. However, in general, radial resonance modes and reverberations in the backing material often lead to variations of ±10 dB in the frequency response between 0,5 MHz and 15 MHz. In addition, the directional response of most ceramic needle **hydrophones** available is often unpredictable and can show significant differences from theoretical predictions. See [41] and [42]. In some cases, however, directional responses of ceramic needle hydrophones were found to be consistent with theoretical predictions [43].

B.9.2 PVDF needle hydrophones

PVDF needle **hydrophones** are similar in external physical construction to the ceramic needle **hydrophones** described in B.9.1. However, the active element is the polymer PVDF. Typically, the **end-of-cable** (1 m) **open-circuit sensitivity** of a PVDF needle **hydrophone** with a 1 mm diameter active element is 0,12 µV/Pa and the resonance frequency is beyond 25 MHz. Carefully designed PVDF needle **hydrophones** show a smooth frequency characteristic (±1,5 dB) and a predictable directional response. The effective diameter of such **hydrophones** [44] is often very close to the physical diameter of the active elements. See [23], [42], [43], [44], [45].

B.9.3 PVDF membrane hydrophones

PVDF membrane **hydrophones** consist of a thin film of PVDF stretched across an annular frame. Electrodes are evaporated onto the two surfaces and an overlap region defines the active element after it has been poled. Various designs have been produced offering different degrees of electrical shielding for the active element. Essentially, the membrane transmits most of the ultrasound when the diameter of the membrane is sufficiently large to enable the whole of the ultrasound beam to pass through it. With this design of **hydrophone**, radial resonance modes in the megahertz frequency range are eliminated, and hence they exhibit a smooth frequency response. Typically, for a 1 mm diameter active element, the **end-of-cable** (0,7 m) **open-circuit sensitivity** of membrane **hydrophones** is about 0,10 µV/Pa and the resonance frequency is at approximately 40 MHz for a 0,025 mm thick film of PVDF. The directional response at all frequencies is predictable, including the low megahertz range where membrane waves in the film give rise to larger side-lobes in the directional response. The effective diameter of such

hydrophones differs from the physical diameter of the active elements and depends on the frequency of the received signal. See [24], [17], [42], [34], [46], [47].

B.9.4 Fibre-optic and optic hydrophones

In the fibre-optic **hydrophones** that have been developed for measurements in medical ultrasound fields, the fibre is aligned so that the end face is normal to the direction of acoustic propagation, just as the element in a piezoelectric needle **hydrophone** would be. In this configuration the fibre behaves as an extrinsic rather than intrinsic sensor, in that its basic function is simply to carry coherent light to the tip where the transduction process is initiated. Three basic designs have been developed to create a reflected light signal that can be related to the acoustic field. In the simplest approach, a bare fibre is cleaved to form a right circular cylinder. In the two other designs, an improvement in sensitivity comparable to piezoelectric polymer **hydrophones** can be achieved by treating the fibre tip, but at the cost of design simplicity and replacement ease. In choosing optic **hydrophones** the following points are of concern.

a) Refractive index change type **hydrophones**, for example fibre tip [39].

   In the simplest approach, light from a laser diode is coupled to a multi-mode fibre with a bare end face. To a good approximation, the light is reflected according to the Fresnel intensity reflection coefficient, $R = [(n_c - n_w)/(n_c + n_w)]^2$, where n_c and n_w are the indices of refraction of the fibre core and water, respectively. Pressure variations in the acoustic wave cause a change in density, which in turn alters the refractive indices, and thus the reflected light intensity. A minimum detectable pressure of 0,5 MPa has been achieved, but this level could possibly be reduced by using signal averaging in cases of repetitive signals, high light source powers or very sensitive photodetectors. The fibre tip has a high damage threshold, but should it be damaged by cavitation, the fibre can be recut without affecting sensitivity. After cleaving, the reflected amplitudes in water and, if possible, in air need to be confirmed to be the same as before damage in order to assure that the sensitivity has not changed. Ideally a check with a reference source of known (sub-damage) output should be performed [12]. An alternative implementation of the refractive change type **hydrophone** uses a thick glass block instead of the fibre tip [48], [49]. Such a device can possibly provide a better low frequency limit in comparison to the diffraction limited fibre-optic version, which is likely to affect the peak rarefactional pressure part of the waveforms determined [50].

b) Two-beam interferometer [51], [52], [53].

   To increase measurement sensitivity, the fibre tip can be mirrored and incorporated into the measuring arm of a two-beam interferometer. The optical phase change caused by the tip movement results in a signal proportional to the acoustic displacement or, when a heterodyne technique is used, the particle velocity, both of which lead to a calculation of the pressure.

c) Fabry-Perot interferometer [54], [55], [56], [57], [58], [59], [60].

   As an alternative to the optical complexity of two-beam interferometry, but still with improved sensitivity compared to the bare fibre design, a Fabry-Perot (FP) interferometer can be formed by attaching an FP cavity to the end of the fibre. When light is sent down the fibre, optical reflections occur at the interfaces between the fibre and the cavity, and the cavity and the load (water). The optical reflection coefficients are determined either by the Fresnel formula for uncoated cavity surfaces or by the type and thickness of metal coatings on these faces.

   Various sources of distortions have been noted in fibre-optic **hydrophones** and several methods to analyse and compensate for these effects have been studied [61], [62], [63], [64].

   In addition to the fibre-optic versions, Fabry-Perot interferometer type **hydrophones** with plane substrates have also been constructed. Advantages of such sensor designs are the possible use as array sensors [65], [66] and the exclusion of acoustic resonance and diffraction effects of the fibre body from the frequency response [67].

B.9.5 Relative performance of different types

The choice of a particular type of **hydrophone** for a specific task will depend on a number of factors. As there is a large variety of designs of **hydrophones** of all basic constructional types, it is not possible to produce simple guidelines for choosing the most appropriate one. However, the following points are worth noting.

a) A membrane **hydrophone** will exhibit less variation in its frequency response than a needle **hydrophone**.

b) The sensitivity of a **hydrophone** with a ceramic active element will usually be higher than one with the same diameter active element made from PVDF.

c) In the case of membrane **hydrophones**, the membrane constitutes a large, plane obstacle of finite reflectivity in the ultrasonic field. The reflected part of the ultrasonic wave might return in a coherent way to the **ultrasonic transducer** and react on it by acoustic interference [68]. This is particularly important in continuous wave excitation of **ultrasonic transducers**, and this source of error should be kept in mind, although its effect on measurements can usually be minimized. In all types of needle **hydrophone**, the effect of reflections is present but to a smaller extent.

B.10 Typical specification data for hydrophones

Examples of typical properties of certain **hydrophone** types are given in Table B.1.

Table B.1 – Typical specification data for hydrophones, in this case given at 1 MHz [69]

Hydrophone type	**End-of-cable loaded sensitivity** **(with a specified load Z_L)** $\underline{M}_L(f)$ µV/Pa	**Electric load resistance and parallel capacitance** **(specified load)**	**Cable length** m	**End-of-cable capacitance** C **or** **End of cable resistance and parallel capacitance**	**End-of-cable open-circuit sensitivity** $M_c(f)$ µV/Pa
PVDF needle 1 mm diameter	0,100	1 MΩ 30 pF	1	130 pF	0,123
PVDF needle 0,6 mm diameter	0,032	1 MΩ 30 pF	1	130 pF	0,039
PVDF membrane 1 mm diameter	0,098	50 kΩ 5 pF	0,7	8,9 Ω 128 pF	0,102
PVDF membrane 0,5 mm diameter	0,033	50 kΩ 5 pF	0,7	12 kΩ 97 pF	0,035
Ceramic needle 1 mm diameter	0,56	1 MΩ 30 pF	1	150 pF	0,67

Annex C
(informative)

Acoustic pressure and intensity

Traditionally, ultrasonic fields have been characterized by the parameter of intensity and this is appropriate and directly relevant for many applications.

However, the **instantaneous intensity** $I(t)$ may be given by

$$I(t) = p(t)\ v(t) \tag{C.1}$$

where

$p(t)$ is the **instantaneous acoustic pressure**;

$v(t)$ is the particle velocity.

Under conditions of plane progressive waves, the **instantaneous intensity** is given by either Formula (C.2) or Formula (C.3):

$$I(t) = p(t)^2/\rho c \tag{C.2}$$

$$I(t) = \rho c\ v(t)^2 \tag{C.3}$$

These expressions have only limited validity and cannot generally be applied throughout an acoustic field. However, Formula (C.2) is almost exclusively used to derive **instantaneous intensity** from **hydrophone** measurements of **instantaneous acoustic pressure**.

To illustrate the significance of this, it can be shown (see [70]), for example, that the ratio of the true intensity to the plane wave approximation value is 0,66 at a distance of 5 mm from the face of a circular plane piston **ultrasonic transducer** of diameter 30 mm and in continuous wave operation. At a distance equal to the diameter of the **ultrasonic transducer**, the ratio is about 0,94.

It is for these reasons that this document recommends the specification of acoustic pressure parameters and, as such, these are the measured parameters appropriate to any acoustic field.

For the determination of derived intensity from acoustic pressure, the values of ρ, c and ρc for distilled or de-ionized water, as a function of temperature, given in Table C.1, may be used.

Unlike peak pressure parameters, derived intensity data do not depend on phase data of the pressure spectra due to the quadrature of the pressure data and Parseval's theorem [36]. Thus, for the determination of derived intensity from acoustic pressure using waveform deconvolution (see Annex D), phase response data of the **hydrophone** is not required, e.g. a constant phase of zero versus frequency can also be used.

Table C.1 – Properties of distilled or de-ionized water as a function of temperature [71]

Temperature	Density of the water	Speed of sound in the water	Characteristic acoustic impedance
T	ρ	c	ρc
°C	10^3 kg/m^3	m/s	10^6 kg/m^2/s
16	0,998 9	1 469,4	1,467 8
18	0,998 6	1 476,0	1,473 9
20	0,998 2	1 482,3	1,479 6
22	0,997 8	1 488,3	1,485 0
24	0,997 3	1 494,0	1,490 0
26	0,996 8	1 499,3	1,494 5
28	0,996 2	1 504,4	1,498 7

Annex D
(informative)

Voltage to pressure conversion

D.1 General

The relationship between the pressure experienced by a **hydrophone** and the voltage it produces at its output is related through the **end-of-cable loaded sensitivity** of a **hydrophone**, and often the **end-of-cable loaded sensitivity** of a **hydrophone** will have been determined over a wide frequency range. This document provides a method to convert the measured end-of-cable voltage $u_{\mathrm{L}}(t)$ produced by the **hydrophone** back to an **instantaneous acoustic pressure** $p(t)$ according to Formula (D.1):

$$p(t) = u_{\mathrm{L}}(t) \,/\, |\underline{M}_{\mathrm{L}}(f_{\mathrm{awf}})| \qquad \text{(D.1)}$$

if the frequency response of the **hydrophone** meets the criteria in 5.1.7.1 and

$$p(t) = \mathcal{F}^{-1}[\underline{U}_{\mathrm{L}}(f) \,/\, \underline{M}_{\mathrm{L}}(f)] \qquad \text{(D.2)}$$

otherwise (see 5.1.2).

The rationale behind this approach is that Formula (D.1) is only valid if:

– the acoustic field generated by the **ultrasonic transducer** has a very narrow frequency **bandwidth**, or

– the **end-of-cable loaded sensitivity** of the **hydrophone** across the **bandwidth** of the **hydrophone** does not vary significantly from the **end-of-cable loaded sensitivity** measured at the **acoustic-working frequency**.

In all other cases, the frequency response of the **hydrophone** is deconvolved from the end-of-cable voltage using Formula (D.2). These requirements contribute to the **bandwidth** specifications of 5.1.7.2.

The **end-of-cable loaded sensitivity**, $\underline{M}_{\mathrm{L}}(f)$, is a complex-valued quantity but it has historically been supplied as a magnitude-only quantity. However, there are now several national standards and other laboratories capable of measuring the phase response of **hydrophones** in broad frequency ranges, and the deconvolution process according to Formula (D.2) can make use of this additional data. See [17], [18], [34], [35], [36], [72], [73].

An alternative approach to measuring **hydrophone** phase response is the computation of phase response data from modulus response data. A minimum phase system can be assumed for some **hydrophones**, which allows an estimation of the frequency-dependent phase response using, for example, Hilbert-Transform methods or iterative phase signal reconstruction techniques [73], [74], [75].

A straightforward easy-to-implement method of calculating the discrete phase response data $\arg\underline{M}(f_m)$ in rad from modulus response data for minimum phase systems is provided by the Bode gain-phase relation formulation [76], which can be written here as Formula (D.3):

$$\arg \underline{M}\left(f_m\right)=\frac{2 f_m}{\pi} \sum_{n=0}^{N/2} \frac{\ln\left(\left|\underline{M}\left(f_n\right)\right| / \left|\underline{M}\left(f_m\right)\right|\right)}{f_n^2-f_m^2} \cdot \Delta f \quad \text{(D.3)}$$

where n and m run from 0 to $N/2$, $n \neq m$, N denotes the number of time signal data points (resulting in $N/2 + 1$ frequency domain data points in the single-sided spectrum, see Clause D.3), f_n and f_m denote discrete frequencies, and Δf is the constant frequency increment, e.g. $\Delta f = f_{n+1} - f_n$.

NOTE Depending on the sign convention of the Fourier transformation algorithm used, the phase response calculated with Formula (D.3) possibly needs to be inverted, e.g. needs to be multiplied with −1. A wrong sign will lead to waveforms obscured during deconvolution showing non-physical additional oscillations and, thus, can easily be spotted in a test application.

The methods of phase calculation from modulus responses may also be helpful when used in combination with measured **hydrophone** phase data to correct the phase calibration data for linear-with-frequency terms by this comparison. Furthermore, it may be used to adequately extrapolate the measured data below and above the experimentally available frequency ranges by assuming reasonable modulus data for those frequency ranges first, see D.4.2, and then calculating the suitable phase response extrapolation with Formula (D.3). An application example for this method is described in [19].

A calculation scheme including step-by-step guidance and examples can be found in a deconvolution tutorial available through online publication [77]. The tutorial uses freeware software tools only and comprises all necessary procedures for deconvolution and associated **uncertainty** estimation[3].

D.2 Hydrophone deconvolution procedure

The complete process for deconvolving the full frequency response of a **hydrophone** according to Formula (D.2) is shown as a flow diagram in Figure D.1.

3 This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

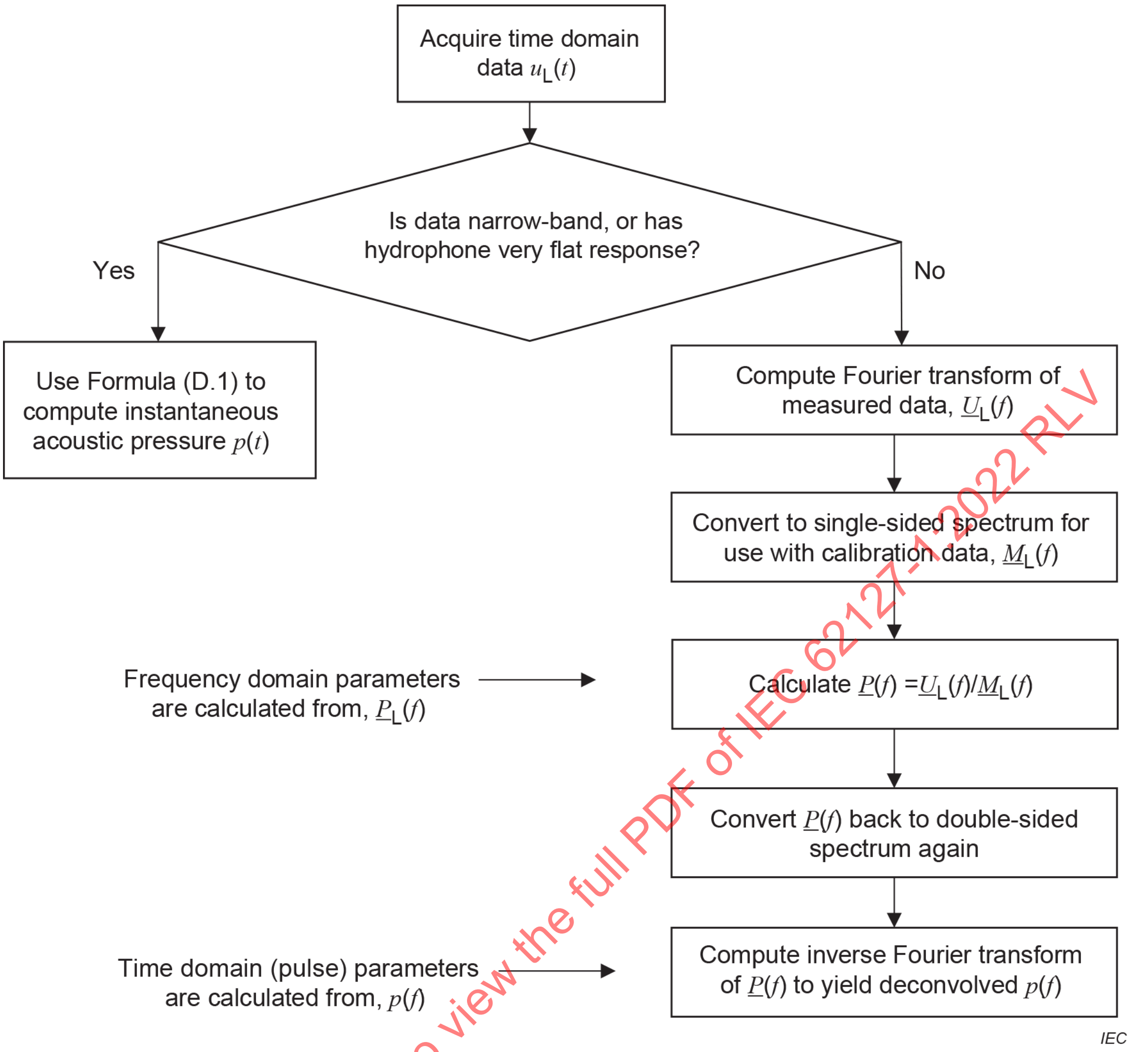


Figure D.1 – A flow diagram of the hydrophone deconvolution process

D.3 Converting the data between double-sided and single-sided spectra

Hydrophone calibration data is typically provided over a range of positive frequency values, whereas conventional fast Fourier transform routines output zero-centred frequency data, with both positive and negative frequency components. Due to the symmetry of the frequency spectrum, the conversion to a single-sided frequency spectrum (containing only positive frequencies) for use in the **hydrophone** deconvolution process should be trivial. In fact, often users are only presented with a single-sided spectrum and may be unaware of the double-sided nature of the original frequency spectra. Unfortunately, several commercial Fourier transform routines do not accomplish this process accurately. A brief description of both the problem and its remedy follows.

Consider a set of data sampled at frequency f_s, and thus having a Nyquist frequency, $f_{Nyquist} = f_s/2$. A typical Fast Fourier Transform (FFT) algorithm will return points ordered such that the first point has frequency f_0 then f_1, f_2, … up to $f_{Nyquist}$. The next point is at $-f_{Nyquist-1}$ and then $-f_{Nyquist-2}$, $-f_{Nyquist-3}$. For all components other than frequency 0 (i.e. DC), the moduli of the positive and negative frequency points are equal, and the single-sided spectrum can be obtained by simply doubling the amplitude of all non-DC components. The complex values of corresponding positive and negative frequency points of the same modulus are complex conjugates. A thorough discussion of the computational issues associated with the Fourier transform is provided by [78].

The problem seen with some commercial routines that conduct the double-sided to single-sided conversion is that they simply halve the size of the data array and double the amplitudes of all but the first component. This is an incorrect method because for a trace of N data points (N being an even positive number), the DC signal is the first data point, with the positive frequencies occupying the next $N/2$ locations in the array. Thus, the data at the (highly important) Nyquist frequency are at location $N/2 + 1$. However, the above method of simply extracting the first half of the data sequence has discarded this point. Failure to include the Nyquist frequency data point will introduce errors and will prevent the inverse Fourier transform process from working properly, as well as introducing significant phase errors. Table D.1 shows the correct method of conducting this conversion.

Table D.1 – Method of conversion from a double- to a single-sided spectrum

Double-sided spectrum Number of points = N Data array = $DS[1..N]$	**Single-sided spectrum** Number of points = $N/2 + 1$ Data array = $SS[1..N/2 + 1]$
$DS[1]$	$SS[1] = DS[1]$
$DS[2]$	$SS[2] = 2 \cdot DS[2]$
$DS[3]$	$SS[3] = 2 \cdot DS[3]$
..	..
$DS[N/2]$	$SS[N/2] = 2 \cdot DS[N/2]$
$DS[N/2 + 1]$ at the Nyquist frequency	$SS[N/2 + 1] = DS[N/2 + 1]$
$DS[N/2 + 2]$	Discard
.. $DS[N]$	.. Discard

Similar care should be taken when converting single-sided spectra back to double-sided spectra for the inverse Fourier transform operation since data points at frequency 0 (DC) and frequency $N/2 + 1$ (Nyquist frequency) appear only once in a double-sided spectrum, whereas all other components appear twice as complex-conjugated values (as both positive and negative frequency components). Table D.2 shows the correct method of converting from a single-sided spectrum back to a double-sided spectrum. SS^* denotes the complex conjugate of SS.

Table D.2 – Method of conversion from a single- to a double-sided spectrum

Single-sided spectrum Number of points = $N/2 + 1$ Data array = $SS[1..N/2 + 1]$	**Double-sided spectrum** Number of points = N Data array = $DS[1..N]$
$SS[1]$	$DS[1] = SS[1]$
$SS[2]$	$DS[2] = SS[2]/2$
$SS[3]$	$DS[3] = SS[3]/2$
..	..
$SS[N/2]$	$DS[N/2] = SS[N/2]/2$
$SS[N/2 + 1]$	$DS[N/2 + 1] = SS[N/2 + 1]$
	$DS[N/2 + 2] = SS^*[N/2]/2$
	$DS[N/2 + 3] = SS^*[N/2 - 1]/2$
	..
	$DS[N] = SS^*[2]/2$

D.4 Use of hydrophone calibration data

D.4.1 Calibration data interpolation

The combination of sampling interval (time increment: Δt) and number of points N acquired determines the frequency interval (frequency increment: Δf) of the spectrum of the measured signal according to Formula (D.4):

$$\Delta f = \frac{1}{\Delta t \times N} \tag{D.4}$$

Frequently, it is found that this frequency increment of the measured data differs from that supplied between consecutive points in the **hydrophone** calibration data. To ensure that calibration data is available at the appropriate frequency points, it may be necessary to interpolate values at the required spacing from the calibration data. Cubic or Bezier spline interpolation routines have been found to be an effective means of providing this additional interpolated data [18]. One of the advantages of these methods is that the interpolation function only needs to be pre-computed once. The interpolation function can then be used to produce calibration data at any required frequency increment. Thus, a refined frequency response curve for each **hydrophone** can be pre-calculated and stored for later use. Alternatively, if **hydrophone** calibration data stem from pulse excitation measurement via Fourier transform, the frequency increment of the data can be adjusted to the application needs by the choice or modification of the signal length in time, e.g. the sample rate and number of data points, within the pulse calibration measurements [34], [35], [36]. For a given sample rate as used in the calibration measurement which determines the maximum frequency (Nyquist frequency), the number of data points may be altered by zero padding afterwards to modify the frequency increment appropriately.

D.4.2 Calibration data extrapolation

For the deconvolution calculation according to Formula (11) or (16), the data sets of the voltage spectrum $\underline{U}_{\mathrm{L}}(f)$ and the sensitivity $\underline{M}_{\mathrm{L}}(f)$ need to cover the same frequency ranges from zero to the Nyquist frequency of the **hydrophone** measurement. For instance, for a typical waveform sampling rate of 500 MS/s (mega-samples per second), data is needed up to 250 MHz. Therefore, extrapolation of $\underline{M}_{\mathrm{L}}(f)$ may be used to cover frequencies f outside the calibration range available if necessary. However, requirements for the frequency range covered by experimental **hydrophone** calibrations are specified in 5.1.7.2.2 to be at minimum from below half of the **acoustic-working frequency** up to four times the **acoustic-working frequency** to ensure that the major portion of the pressure spectrum is evaluated using most reliably confirmed sensitivity data on the one hand, and to allow the application of the method and standard to most applications in practise, where **acoustic-working frequencies** may extend up to 25 MHz and available calibration ranges may reach up to 100 MHz, on the other hand. For **acoustic-working frequencies** larger than 25 MHz, the acceptable upper experimental calibration data limit of 100 MHz can still be retained for practical reasons. For high intensity therapeutic ultrasonic fields usually comprising **acoustic-working frequencies** below 5 MHz, the range opened for extrapolation is reduced in 8.3.2 to beyond 20 f_{awf} because spectra at clinical driving levels comprise far more higher harmonics.

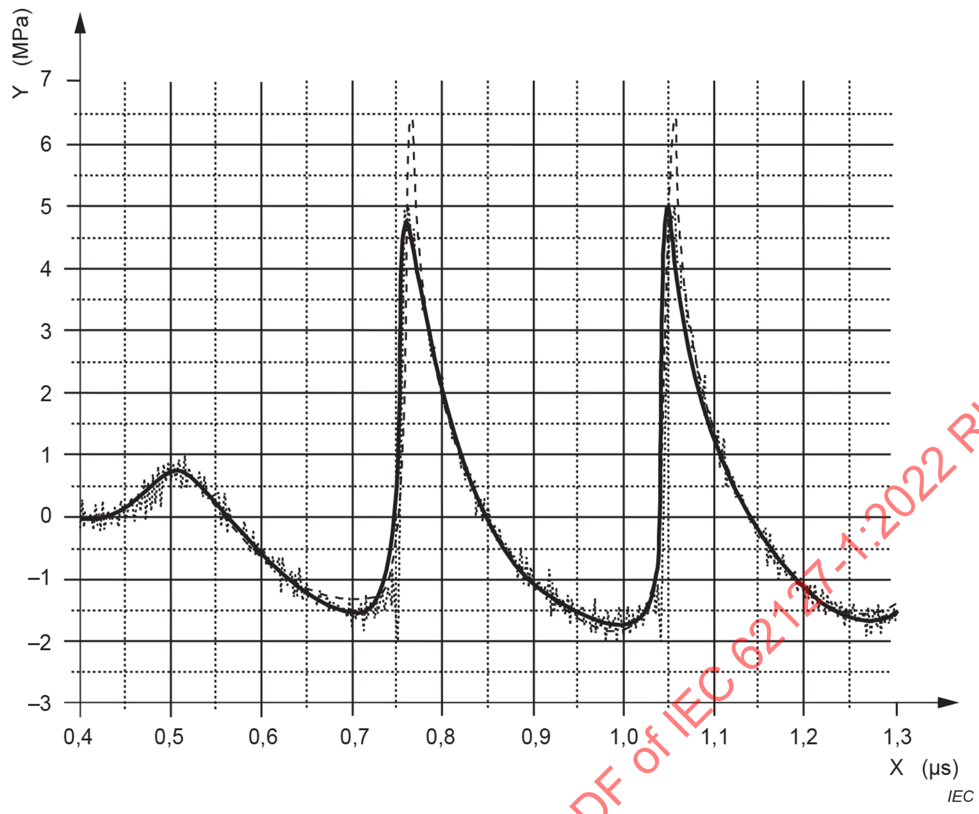
A convenient way may be to start with extrapolating the modulus data first and to adjust the phase data in a second step using Formula (D.3). This will assure consistent complex-valued response extrapolation, including the phase value being zero at zero frequency as is necessary for any real-valued time domain impulse response [20]. The modulus extrapolation should follow the trend indicated by the calibration range limit region; for instance, if some thickness mode resonance behaviour can be observed at the high frequency end a decreasing behaviour with frequency may be estimated from that. Of course, the sensitivity cannot become zero. This would induce singularities in the deconvolution because some noise can be expected in the voltage spectrum even at frequencies not transduced by the **hydrophone** due to zero sensitivity.

Several investigations have shown that rather simple extrapolation schemes work well for most applications, e.g. lead to reasonable deconvolved waveform results. For membrane **hydrophones**, using the lowest calibration data point modulus as constant value down to zero and using the highest calibration data point modulus as constant value above the calibration range may be sufficient [17], [19], [20] and can be applied as standard procedure. However, if the preamplifier is known to cause a significant roll-off at low frequencies, either from manufacturer's specifications or from electrical measurements, such sensitivity decrease should be accounted for in obtaining $\underline{M}_{\text{L}}(f)$. In this case, the extrapolation should include the constant value extrapolation combined with the preamplifier's relative response from the lowest calibration frequency down to $f_{\text{awf}}/16$ (see 5.1.7.1, NOTE 3). From zero frequency to $f_{\text{awf}}/16$, $\underline{M}_{\text{L}}(f)$ can be assumed to equal the value at $f_{\text{awf}}/16$. For needle type and fibre-optic **hydrophones**, a decreasing sensitivity towards low frequencies can be expected due to the impact of diffraction at the sensor tip. Here, decreasing sensitivity modulus functions show good results and should be applied [18], [79]. If available, more comprehensive **hydrophone** frequency response modelling may be used for the purpose of extrapolation. Relatively simple secondary impulse calibration methods [11], [12] can also be applied by the hydrophone user to extrapolate sensitivity data reasonably, as can measurements of similar units of the same design (see 5.1.7.2.2, NOTE 2 and NOTE 3).

The **uncertainty** introduced to the measurement by extrapolating the calibration data can be assessed together with the regularization error (see D.4.3) using an upper bound function estimation method for the pressure spectrum [14].

D.4.3 Regularization filtering

Mathematically speaking deconvolution is an ill-posed inverse problem [13], [14]. To avoid excessive additional high frequency noise in the deconvolved waveforms, regularization filtering may be necessary. Such noise can arise from low **hydrophone** sensitivity (at high frequencies) and from the Gibbs phenomenon. Appropriate suppression may be achieved by low-pass filtering of the pressure pulse spectrum prior to the back transformation to the time domain. Figure D.2 shows an example waveform obtained in Doppler mode of a diagnostic ultrasound machine with voltage to pressure conversion using narrow-band approximation, deconvolution, and deconvolution with additional low-pass filtering in comparison. Deconvolution removes the strong overshoot of the waveform in the peak compressional parts of the wave obtained when using the narrow-band approximation and caused by the **hydrophone** thickness mode resonance at high frequencies. However, the deconvolution also introduces high frequency noise and artificial rarefactional pressure peaks in front of the steep pressure steps (Gibbs oscillations). Using the additional regularization filtering, the additional noise and high frequency oscillations are appropriately removed. On the other hand, any additional low-pass filtering causes additional effective limitations of the detection **bandwidth** and, in particular, peak compressional parts of nonlinearly distorted ultrasonic waveforms incorporating high frequency components may possibly be cut. Requirements for the filtering are provided in 5.1.7.2 including guidance on how to include in the **uncertainty** analysis the systematic error introduced through regularization for parameters derived from the deconvolved **acoustic pulse waveforms** [14], [21].



Key

X time

Y pressure

NOTE The example shows part of a Doppler pulse measured by a needle hydrophone. The voltage to pressure conversion uses (dashed line) $\underline{M}_L(f_{awf})$, (···) using deconvolution $\underline{M}_L(f)$, and (solid line) deconvolution with additional low-pass filtering (−6 dB at 80 MHz).

Figure D.2 – Example of waveform deconvolution

D.5 Implication of the hydrophone deconvolution process on measurement duration

Many acoustic reporting parameters require that a **hydrophone** will have been scanned through the acoustic field, and these measurements can be time-consuming. Figure D.2 tends to suggest a significant increase in the measurement time overhead. However, if implemented correctly, this process does not add any significant increase to the total measurement duration.

The majority of automated scanned **hydrophone** acquisition systems are PC-controlled, and, although digital oscilloscopes have a range of on-board processing capabilities, much of the data post processing is done by PC. The key to ensuring the deconvolution is a time effective process to ensure that the processing of data transfer to the PC is done while the **hydrophone** is being moved to its next location within the acoustic field. Once the data is on the PC, the remainder of the deconvolution process (two Fourier transforms and a division) can be done rapidly. In fact, with efficient implementation, the processing can be done fast enough to give real-time feedback of deconvolved waveforms to the user, which can in turn lead to better alignment on spatial-peak features within the acoustic field.

D.6 Validation of deconvolution implementation

There are several possibilities to validate the correct implementation of the numerical deconvolution procedure. The validation should be performed using example measurement data of a broadband pulse. First of all, the waveforms obtained using the deconvolution should be compared with those using the narrow-band assumption on the same **hydrophone** voltage data. If the implementation comprises major errors like, for instance, a wrong sign in the phase term of the Fourier transform algorithm, this can be observed easily through the appearance of unexpected waveforms with extra oscillations that physically make no sense. For typical waveforms and **hydrophones**, only slight differences would be expected in the rarefactional parts of waveforms, and typical overshoots in the compressional parts should be removed by the deconvolution. Other computational errors often result in significant time-shifts or inversion of the signal, all of which are also easily spotted through such comparisons.

The second method of validation of the implementation is to use a broadband **hydrophone** with flat frequency response for comparison measurement of a typical broadband pulse waveform. Membrane **hydrophones** with foil thicknesses from 4,5 µm to about 12 µm are available that provide very flat frequency responses up to 70 MHz and beyond and can be applied as reference.

Finally, a pulse check source or a reference transducer system for which waveforms have already been measured with a broadband **hydrophone** or using already validated deconvolution can be applied for validation. Metrology institutes and measurement equipment manufacturers may offer corresponding waveform measurement services for such reference transducer systems.

A publicly available deconvolution tutorial including stored example reference data sets for **hydrophone** calibration data, **hydrophone** signal voltage data, and corresponding deconvolved pressure waveforms including **uncertainty** estimates is available [77] and can be used for validation of custom made numerical implementations[4].

4 This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

Annex E
(informative)

Correction for spatial averaging

E.1 Linear and quasilinear fields

For most measurements made on diagnostic ultrasonic fields, the diameter of the active element of the **hydrophone** is comparable with the width of the ultrasonic beam and the **hydrophone** measures the average acoustic pressure over the area of its active element rather than the pressure at the centre of its active element. The difference depends on the spatial variation of the ultrasonic field. To correct for this spatial averaging effect, a simple method has been developed [80], [81], which utilizes beam-plots obtained with a step size equal to one **hydrophone size**. A number of other similar methods can also be applied [37], [38], [82], [83], [84], [85].

The procedure for determining corrections makes the following assumptions.

a) The **hydrophone** output is proportional to the acoustic pressure averaged over its active element, which is assumed to be a circular area having a radius equal to the geometrical radius.

b) The radial field distribution, usually in the focal plane of the transducer, from the axial peak to a distance equal to the radius of the active element of the **hydrophone**, can be modelled by a quadratic function: $p(r) = 1 - \mathrm{b}r^2$ where b is a constant. The limits on the accuracy of this correction are determined by assuming that the true beam shape is described by a Bessel function:

$$p(r) = \frac{2\mathrm{J}_1(kar/d)}{(kar/d)} \qquad \text{(E.1)}$$

where

k is the circular wave number;

a is the transducer radius;

r is the distance from the axis in the focal plane;

d is the focal distance;

J_1 is the Bessel function of the first kind, of order 1.

c) The correction procedure for a sawtooth waveform (one distorted by nonlinear propagation) is not the same.

Under these assumptions, the correction factor, K_{sa}, at the centre of the beam is:

$$K_{\mathrm{sa}} = (3 - \beta)/2 \qquad \text{(E.2)}$$

where

β is the signal at one **hydrophone** radius from the axis divided by the signal on axis.

The correction should be based on the average value of β determined in two perpendicular oriented directions.

This formula is obtained by convolving the response of the **hydrophone** with the assumed true field profile for the two measurement positions and relating β to the ratio of the true pressure to the measured value on axis. The procedure for determining the correction $\delta = (K_{sa} - 1)$ is valid for $\beta > 0{,}8$; this corresponds to using a **hydrophone** with a radius that is less than 0,6 times the −6 dB beam radius. For currently available **hydrophones** with 0,5 mm diameter active elements, the correction is less than 10 % provided that the −6 dB beam radius is greater than 0,4 mm.

Because this correction method might not be valid in the case of sawtooth waveforms (i.e. distorted by nonlinear propagation) another formula may be more valid [81].

The correction factor, K'_{sa}, at the centre of the beam is:

$$K'_{sa} = (3 - 2\,\beta') \tag{E.3}$$

where

β' is the signal at half a **hydrophone** radius from the axis divided by the signal on axis.

The correction should be based on the average value of β' determined in two perpendicular oriented directions.

NOTE 1 "Signal" in the above definitions of β and β' represents p_c, p_r or $ppsi^{1/2}$. For each of these quantities a different K_{sa} or K'_{sa} can be expected. The correction factor for intensity related values derived from $ppsi$ is given by the square of K_{sa} or K'_{sa}, where these are derived using $ppsi^{1/2}$.

NOTE 2 In a number of cases, the $ppsi^{1/2}$ is replaced by any linearly related quantity, e.g. in the case of a continuous wave signal the term $ppsi^{1/2}$ is replaced by **RMS acoustic pressure.**

The **uncertainty** of the correction $\delta' = (K'_{sa} - 1)$ is estimated to be 10 % for $\beta' > 0{,}92$.

NOTE 3 The overall **uncertainty** can also depend on the actual (not necessarily symmetric) geometry of the **hydrophone's** active element.

Note that the effective diameter of well-designed PVDF needle **hydrophones** is readily predictable. For membrane **hydrophones**, the response is more complicated and, in some cases, and at low frequencies, the geometrical radius of the membrane **hydrophone** might not be equal to the **effective hydrophone size** as determined from directional response measurements (see [42]). In this case, the procedure is modified by moving the **hydrophone** by its effective radius instead of its geometrical radius.

Experimental results using a number of **hydrophones** of different size of active element [31] showed that for most focused ultrasonic fields the procedure given above underestimates the correction. Other studies [86] have shown that the major reason for the underestimates is the residual presence of nonlinear distortion in the fields.

Studies have shown [86] that, providing $\delta_m < 0{,}5$, the correction procedure given above will provide reasonable estimates of the spatial averaging correction for all acoustical parameters within **uncertainties** of 10 % to 15 %. For more distorted waveforms, it is possible to delineate the following regimes for estimation of spatial averaging corrections in terms of the parameter R_{bh}, the ratio of the −6 dB **beamwidth** to the effective **hydrophone** diameter. Guidance for the magnitude of the likely corrections for the **peak-compressional acoustic pressure** p_c, **peak-rarefactional acoustic pressure** p_r, and **pulse-pressure-squared integral** $ppsi$, are as follows [86]:

$$R_{bh} > 2$$

NOTE 4 The referenced study used the nonlinear propagation parameter σ_m for characterizing the amount of nonlinear distortion. However, IEC 62127-1:2007/AMD1:2013 changed to using the **local distortion parameter** σ_q instead. In typical applications both parameters have similar values. Therefore, for the purpose of the estimates here, σ_m can be replaced by σ_q.

For 0,5 < σ_m < 1,5 the maximum p_c and p_r corrections will be approximately 13 %, with the correction to $ppsi$ being less than 25 %; for σ_m > 1,5, the peak pressure corrections will be higher but are unlikely to exceed 20 %.

$$1{,}5 \le R_{bh} \le 2$$

For σ_m < 1,5, the corrections to p_c and p_r will be less than 20 % while the correction to $ppsi$ will generally not exceed 40 %. For higher σ_m values, corrections to p_c, p_r and $ppsi$ can be greater than 30 %, 20 % and 50 %, respectively.

$$R_{bh} < 1{,}5$$

In this regime, large spatial averaging effects occur for all parameters but particularly for p_c and p_r at all values of σ_m, corrections for p_r can reach 50 % but these are not significantly different from the values obtained from the procedures given above. In contrast, p_c corrections can be of the order of 100 % for 0,5 < σ_m < 1,5, and for σ_m > 2 can be in excess of 200 % corresponding to $ppsi$ corrections of 300 %. Therefore, in situations where R_{bh} < 1,5, it is important that a smaller **hydrophone** be used for measurements.

E.2 Linear fields, quasilinear fields, and broadband nonlinearly distorted waveforms

An inverse spectral filtering approach may be used to correct for spatial averaging effects for linear beams or nonlinear beams that contain multiple harmonics of the fundamental frequency. The inverse spectral filtering approach is more general than the method in Clause E.1. The method in Clause E.1 assumes linear propagation. The inverse spectral filtering approach allows for linear or nonlinear propagation. The two methods give similar results for the spatial averaging correction at fundamental frequency, as shown in Figures 3 to 5 in reference [87]. In addition, the inverse spectral filtering approach gives appropriate spatial averaging corrections at harmonic frequencies for nonlinearly distorted waveforms. Another advantage of the inverse spectral filtering approach is that it does not require a separate off-axis **hydrophone** measurement. The effects of spatial averaging can be described by a spatial averaging filter $\underline{S}(f)$, which gives the frequency domain ratio of the spatially averaged **hydrophone** output to the signal that would be measured by an ideal point **hydrophone**. The **hydrophone** spatiotemporal response is assumed to be separable into a product of spatial and temporal factors, and extending Formula (11) or (16), the actual acoustic pressure corrected for both the spatial averaging effect and the effects of varying sensitivity is then calculated from Formula (E.4):

$$p(t) = \mathcal{F}^{-1}\left(\underline{LP}(f) \cdot \frac{\underline{U}_L(f)}{\underline{M}_L(f) \cdot \underline{S}(f)} \right) \tag{E.4}$$

The spatial averaging filter at each harmonic frequency depends on the ratio of the frequency-dependent **effective hydrophone size** to the frequency-dependent harmonic **beamwidth**. For harmonics with Gaussian-shaped radial profiles and assuming constant phase of $S(f)$, it can be shown that the spatial averaging filter is given by [87], [88], [89]

$$S(nf_1) = \frac{1 - \exp\left(-\Omega_n{}^2\right)}{\Omega_n{}^2} \tag{E.5}$$

where f_1 is the fundamental frequency and n the harmonic number, and

$$\Omega_n{}^2 = \frac{a_{\text{eff}}{}^2(nf_1)}{2\sigma_n{}^2} \ , \tag{E.6}$$

where $a_{\text{eff}}(nf_1)$ is the frequency-dependent **effective hydrophone size** evaluated at fundamental and harmonic frequencies, and σ_n describes the harmonic **beamwidth** parameter for a harmonic with radial profile shaped like $\exp(-r^2/2\sigma_n{}^2)$; r is the radial coordinate.

The frequency-dependent radius $a_{\text{eff}}(nf_1)$ can be evaluated from directivity measurements at multiple frequencies (IEC 62127-3:2007, 5.5 and 5.6). Alternatively, for needle or reflectance-based fibre-optic **hydrophones**, an experimentally-validated theoretical form for $a_{\text{eff}}(nf_1)$ can be used [43], [87]. For membrane **hydrophones**, an empirical formula for $a_{\text{eff}}(nf_1)$ can be used [34], [90].

The **beamwidth** parameter σ_n can be obtained from theory, simulation, or experiment. In many cases relevant to medical ultrasound (nonlinear distortion not too severe), the fundamental beam will be similar in shape to the prediction based on linear propagation theory. Then σ_1 can be obtained by fitting a Gaussian function to the theoretical diffraction pattern from a focused, circular source, which results in σ_1 = 1,93 $D/(k_1 a_s)$, where D is the radius of curvature or focal distance, $k_1 = 2\pi/\lambda_1$, λ_1 is the fundamental wavelength, and a_s is the radius of the source [87].

In many cases relevant to medical ultrasound, the dependence of harmonic **beamwidth** on harmonic number can be accurately approximated by a power law, $\sigma_n = \sigma_1/n^q$ [87], [91]. The value of the exponent q depends on the degree of nonlinearity of the pressure signal, which can be described by the **local distortion parameter** σ_q. Simulation and experiment suggest that for $\sigma_q < 6$, q can be approximated by q = 0,78 − 0,032σ_q [87]. This formula has been shown to be valid even for high intensity therapeutic ultrasound signals with **peak compressional acoustic pressures** up to 48 MPa [91].

The combined effects of frequency-dependent sensitivity and spatial averaging for needle and reflectance-based fibre-optic **hydrophones** have been illustrated in a 27-panel graphical guide that can be used as an aid in choosing an appropriate **hydrophone geometrical radius** for a given measurement task [87].

While the method in Clause E.1 provides the spatial averaging correction at the centre frequency of a linear, narrow-band waveform, the method in Clause E.2 provides the spatial averaging filter at the fundamental and harmonics for linear and nonlinear waveforms. The method of Clause E.2 has been validated in experiments using nonlinear tone bursts [88]. Though the method has been verified only for a burst wave, it is considered to still be useful for a pulse wave. For short pulses (only a few cycles or less in duration), simulation has been used to determine the spatial averaging filter to frequencies also between harmonics [92]. The spatial averaging correction factor has been found to oscillate with local minima at the fundamental and harmonics and local maxima midway between harmonics [36], [92]. For quasi-linear beams and for waveforms comprising only one nonlinearly distorted wave cycle (sawtooth-like cycle), the magnitude of the oscillation is small (< 10 %). For highly nonlinear waveforms with more than one distorted wave cycle, the oscillation is greater due to interference effects of the higher frequency components stemming from different parts of the waveform [92].

Annex F
(informative)

Acoustic output parameters for multi-mode medical ultrasonic fields in the absence of scan-frame synchronization

F.1 General

The earliest clinical ultrasound scanners used fixed-focus, single crystal transducers to generate the ultrasound field. This transducer was either held stationary (for A-mode or M-mode operation), or mechanically moved from side to side (for B-mode operation). The invention of phased, linear-arrays allowed the focusing to be electronically controlled and, for B-mode, scanning to be carried out electronically. Static Doppler (D-mode or PWD, pulsed wave Doppler) and colour-flow imaging (CF-mode) have also been introduced and available for 15 years or more. In the last few years, harmonic imaging, CT-imaging and 3-D imaging have all appeared. To further add to the plethora of output configurations, each of these modes can, in principle and often in reality, be combined with any other mode or combination of modes. And yet, prescribed measurement methods have not moved on. All the major national and international standards relating to measurement of acoustic output were published in 1993 or before and were largely formulated several years before that. The methods, which seemed adequate for the majority of purposes at the time, are now extremely time-consuming to carry out and often impossible. There is now a need to reconsider the existing parameter definitions and measurement methods and perhaps to develop new ones more appropriate to modern imaging equipment. This Annex F is meant to gain support for a new approach before putting parts into a normative text in future. It can be used in those cases where there does not exist a scan-frame repetition.

F.2 Current philosophy

The approach, or philosophy, behind existing measurement standards goes back to the origins of diagnostic ultrasound when the ultrasound field was generated by a single crystal of fixed geometry. The starting point is that a single type of ultrasound pulse – defined by its **acoustic frequency**, duration and focusing properties – is generated. Each pulse generated is of exactly the same type and is directed either along a single well-defined **beam axis** (in the case of unscanned A-mode, M-mode or D-mode) or along a series of distinct and well-defined axes (in the case of the scanned B-mode or CF-mode). Each of these modes is considered to be a distinct "discrete **operating mode**"; for scanned modes it is assumed that a repeating sequence of pulses will form a "scan-frame" and that each scan-frame will contain exactly the same number of pulses.

For simple discrete modes, this approach works well. For unscanned modes, measurements can be made with a **hydrophone** along the **beam axis** allowing a focal point to be located and a variety of acoustic parameters to be determined. The main basic parameters defined in this document or in IEC 61161 are listed in Table F.1.

Table F.1 – Main basic parameters defined in this document or in IEC 61161

p_c	Peak-compressional acoustic pressure
p_r	Peak-rarefactional acoustic pressure
f_{awf}	Acoustic-working frequency
t_d	Pulse duration
$ppsi$	Pulse-pressure-squared integral
I_{sppa}	Spatial-peak pulse-average intensity
I_{spta}	Spatial-peak temporal-average intensity
w_6	−6 dB beamwidth
I_{sata}	Spatial-average temporal-average intensity
P	Total ultrasonic power
z_{ppsi}	Distance from external transducer aperture to the position of maximum pulse-pressure-squared integral
z_{spta}	Distance from external transducer aperture to the position of spatial-peak temporal-average intensity
prr	Pulse repetition rate
srr	Scan repetition rate

For discrete scanned modes, where the scan-frame consists of N distinct scan lines, it is possible simply to examine every Nth scan line and characterize it in the same way as for an unscanned beam, except that derivation of I_{spta} needs to account for "overlap" between scan lines and derivation of P needs to include the acoustic power for all scan lines. An additional complication arises because, since the overlap between scan lines varies with distance, the position of the maximum I_{spta} will generally not be at the same distance from the transducer as the position of maximum $ppsi$ for any single scan line. It is then assumed that, as the complexity of the field increases, it remains possible to isolate individual discrete modes of regular repeating periods.

F.3 Need for an alternative approach

However, the above approach is only possible if the number of scan lines in the scan-frame remains constant until the scanner controls are adjusted. For many modern scanners, the number of scan lines is constantly changing, which makes it impossible to synchronize the measurement process with the generation of a specific ultrasonic pulse. This means that measurements of mandatory parameters can only be carried out by manufacturers with the equipment operating in dedicated engineering modes. Moreover, these measurements are extremely time-consuming to perform and their value to determining either the performance or the safety of imaging equipment is questionable.

F.4 Proposed approach

F.4.1 Alternative philosophy

The alternative approach suggested here does not require synchronization with the scan-frame. At least the parameters that are relevant to the continued safe use of ultrasound imaging should be included. At present, this means factors that may affect heating and cavitation (or other bubble activity). It needs to be possible to measure these parameters for any field without special knowledge of the scanner (although it would be expected that such knowledge will allow measurements to be carried out more rapidly). However, it should also be possible to use existing measurement methods and infrastructure and to calculate values for the field by an appropriate combination of quantities for the individual pulses.

This is an important consideration because it allows manufacturers and other laboratories to continue to use their existing measurement infrastructure.

As far as possible, the required acoustic parameters will be based on a subset of the existing parameters defined by IEC but modified to account for the change of philosophy, which means that the field no longer consists of a repeating pattern of discrete pulses each of a well-defined centre frequency.

F.4.2 Alternative parameters

For systems that do not meet the narrow-band requirements, recording of the time waveform is required and any correction required or recommended in other clauses of this document for limited **bandwidth** or finite sensor dimensions should be applied also. However, the new parameters are mostly chosen so that, for a system that does meet the narrow-band requirements, they can be determined with a system which can only measure peak pressures and RMS voltage.

NOTE In general, diagnostic and high intensity focused ultrasound (HIFU) equipment meets the narrow-band requirements at maximum output levels only via a broadband flat **hydrophone** frequency response, see 5.1.7.

The exception to this is the **acoustic-working frequency** which, as at present, will require the ability to carry out spectral analysis. Table F.2 presents a list of parameters that are to be used or are to be deleted.

Table F.2 – List of parameters that are to be used or are to be deleted

p_c	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
p_r	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
f_{awf}	Calculate from pressure spectrum measured over 1 s or more, or from Fourier analysis of the pulse containing the peak negative pressure (see below for more details). For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
t_d	Not required. The existing definition of pulse duration makes measurement of it subject to substantial **uncertainty** and error depending on the frequency response of the measurement system. Moreover, a single value for pulse duration is only relevant if all acoustic pulses are identical.
$ppsi$	Not required. Pulse-intensity integral is currently used to define the axis and focus of individual pulses and to calculate spatial-peak pulse-average intensity.
I_{sppa}	Not required. Spatial-peak pulse-average intensity is subject to large **uncertainties** due to the definition of pulse duration. Since it is unlikely to be of direct relevance to safety, this parameter can be dropped. The limit placed on I_{sppa} by the Food and Drug Administration in the USA in their FDA510(k) should be removed completely or replaced with a limit on Mechanical Index (MI) or p_r.
I_{spta}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
w_6	Calculated from I_{spta} and p_r distributions, not from $ppsi$. The diameter of an individual ultrasound beam may be of interest for some aspects of performance but is not relevant for safety. The diameter of the temporal-average intensity and peak-rarefactional acoustic pressure distributions, however, are relevant to safety. Beam areas (which are used in the definition of I_{sata}) can be defined on the same basis. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
I_{sata}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.

P	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
z_{ppsi}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
z_{spta}	As in current definition. For a single, fixed-beam mode, the numerical result will be identical to the existing definition.
prr	Not required.
srr	Not required.

F.5 Measurement methods

F.5.1 General

Measurements will be made with an appropriate **hydrophone assembly**. Observation at any point should be carried out for long enough that a fully representative part of the acoustic signal is sampled. Typically, this would be less than 1 s.

New technology oscilloscopes and digital capture cards are now available which allow extremely long recording lengths to be captured and analysed. In general, use of such a device is likely to be the most flexible way to determine all the necessary parameters. Since it is no longer assumed that the acoustic signal will repeat, equivalent-time sampling is not possible and consequently the single-shot digital **bandwidth** will need to be sufficient to accurately represent the **hydrophone** signal.

F.5.2 Peak pressures

Many acoustic pulses can be captured and a search carried out for the peak positive and negative values. Pulses above a certain threshold can be captured selectively. As a simpler alternative, a suitable "envelope" mode or peak-detect circuit can be used.

F.5.3 Temporal-average intensity

The most general method is to digitize every acoustic pulse and calculate the **temporal-average intensity** from this data. Clearly, this will be easier if an electrical trigger signal corresponding to each acoustic firing is available. In the absence of such a trigger signal, capture can be initiated by triggering on the waveform or simply by initiating a continuous acquisition sequence. In these latter two cases, it may be necessary to pre-process the waveform data to minimize electrical noise and to remove non-acoustic signals.

NOTE In many cases, a very high sample rate is not expected to be required to measure I_{spta} since the energy in the N^{th} nonlinear harmonic is less than or equal to $1/N^2$ times the energy in the fundamental.

In principle, I_{ta} can be measured more simply with an RMS voltmeter (or radio frequency power meter) fitted with an appropriate voltage sensor. In practice, electrical noise and the temporal response of the sensor may cause some difficulties at lower levels of I_{ta}. However, for most clinical fields where I_{spta} approaches the current FDA510(k) limits of 720 mW cm^{-2} (derated), it is possible to use this method to locate and measure the peak value and to measure the −6 dB **beamwidth**.

F.5.4 Frequency

From the perspective of a safety standard, we can consider two different reasons for wanting to know the **acoustic frequency**. The first relates to the occurrence of cavitation and its relevant quantity is approximately the centre frequency of the pulse with the largest negative pressure. The second reason relates to heating and the relevant quantity is approximately the median of the acoustic pressure spectrum. In single mode operation, these two quantities are likely to be similar. However, for combined modes, these two quantities may be significantly different. For instance, in B+CF imaging, the scan-frame generally consists of a small number of short, high amplitude pulses for grey-scale imaging and a larger number of longer, lower amplitude Doppler pulses. The centre frequency of each type of pulse may lie anywhere within the **bandwidth** of the transducer.

Consequently, two distinct frequency parameters are suggested for each of these two requirements.

- Mechanical acoustic frequency is determined at the point where the negative pressure reaches its global maximum value. This frequency is defined as **peak pulse acoustic frequency** f_p.
- Thermal acoustic frequency is determined at the position where the temporal-average intensity reaches its global maximum value. This frequency is defined as temporal-average acoustic frequency f_t.

NOTE 1 It can be necessary to correct for frequency-dependent sensitivity of the **hydrophone** and amplifier in order to correctly determine the time averaged acoustic pressure spectrum, especially in cases where there are two or more widely separated spectral peaks of similar magnitude.

NOTE 2 The detailed procedure to obtain the appropriate acoustic power spectrum has not yet been elaborated.

F.5.5 Power

Power should be measured with a radiation force balance or by planar scanning with an appropriate **hydrophone**.

F.6 Discussion

F.6.1 Relationship to existing standards

F.6.1.1 IEC 61157

A change would be that, while measurements would still be made at the position of the maximum **peak-rarefactional acoustic pressure** p_r, the other location would now be at the position of the maximum spatial-peak temporal average intensity, I_{spta}, rather than at the maximum of the pulse-pressure-squared-integral for a single pulse type.

The exemption clause for low output equipment would remain and would be based on the same parameters as currently specified, except that the definition of **output beam area** would need to be altered to refer to I_{spta}. This may affect the value of I_{ob} for some scanned systems, but not for the unscanned systems that generally fall into the exempt group.

F.6.1.2 IEC 62359 and IEC 60601-2-37

In principle, these would not be greatly changed. The major difference would be in the calculation of those Thermal Index (*TI*) formulae that depend on the variation of intensity with distance along the axis. Currently, the *TI* for each type of pulse is calculated independently and combined in a not altogether satisfactory way to arrive at a value for the scan pattern. With the new approach, the temporal-average intensity for the entire scan-pattern is measured (or calculated) and the axial variation of this quantity determines the distance and the value of the *TI*. This change would also be carried through to calculating the equivalent beam diameter as a function of distance. A further minor change would be in the value used for the **acoustic-working frequency**, which affects the derating calculation and is also used explicitly in the soft tissue *TI* calculations. The alternative approach is actually a more consistent implementation of the *TI* concept and, for unscanned fields, the results should be identical.

For the Mechanical Index (*MI*), the value of the frequency used in the formula may be different in some cases.

F.6.2 Advantages

The major benefits appear to be substantial.

- The number of measurements required and the number of declared parameters are greatly reduced since only two sets of measurements are now required for each probe, instead of two sets for each operational mode of each **ultrasonic transducer**.
- The definitions of the new parameters can be applied to even more complicated output patterns and sequences in the future as new imaging techniques are developed.
- Measurements on even complex **operating modes** can be made with relatively straightforward measuring equipment.

Existing measurement methods can still be used and should generate consistent results. For simple, unscanned systems (and perhaps for many others), the values of the acoustic quantities will be unchanged from the existing definitions.

F.6.3 Disadvantages

The technical disadvantages include:

- the introduction of a second frequency quantity;
- possible susceptibility of the method to electrical noise;
- possible need to make minor changes to existing measurement techniques and equipment;
- a requirement of significant wave memory for a long-term (> 1 s) sequence.

Annex G
(informative)

Propagation medium and degassing

It is well established that measurements can be strongly affected by acoustic cavitation. Cavitation is the growth, oscillation and collapse of previously existing gas- or vapour-filled microbubbles in a medium. During ultrasonic measurements, these bubbles will scatter the ultrasound from the transducer under test, causing instabilities and underestimates of the values to be measured. There is thus a need to know when cavitation is occurring during measurements, and also to define suitable media in which the effects of cavitation can be minimized.

A measurement method to detect the onset of cavitation is described in [93], [94]. Specifically, the onset of inertial cavitation is often characterized by the presence of the subharmonic of the fundamental operating frequency. An example of an acoustic spectrum acquired using a needle **hydrophone** is presented in [93], [94].

Possible methods to degas the water are investigated in [95] and listed in IEC TR 62781.

Annex H
(informative)

Specific ultrasonic fields

H.1 Diagnostic fields

H.1.1 Useful relationships between acoustical parameters

A number of useful relationships exist between various acoustical parameters, which can be used to check consistency of acoustic output measurements. Some of these are given below.

The **spatial-peak pulse-average intensity**, I_{sppa}, is related to the **spatial-peak temporal-average intensity**, I_{spta}, by

$$I_{sppa} = prp \times I_{spta} / t_d \quad (H.1)$$

To determine the total **ultrasonic power**, the procedures and techniques described in 7.3.2.4 or IEC 61161 may be used. If the total **ultrasonic power**, P, is known, then it is possible to determine values for the **spatial-average temporal-average intensity**, which are over-estimates. If P_{beam} refers to the total power emitted by one acoustic scan line for an automatic scanner then the following equalities and inequalities hold:

$$P = n_{sl} \times P_{beam} \quad (H.2)$$

where

n_{sl} is the total number of acoustic scan lines.

NOTE Formula (H.2) assumes the same **number of pulses per ultrasonic scan line** n_{pps} for each scan line.

For **non-scanning modes**:

$$P/A_b > I_{sata}$$

For **scanning modes**:

$$P/A_{scan} > I_{sata}$$

and:

$$w_{scan} > s_s \times n_{ts}$$

where

I_{sata} is the **spatial-average temporal-average intensity**;

A_{scan} is the scan area;

w_{scan} is the scan width;

s_s is the **ultrasonic scan line separation** (see 3.87).

It is assumed here that the scan lines are equally spaced, which is not necessarily the case. For some types of transducer, such as a linear array, "scan width" represents the width of the scan in a straight line parallel to the linear array surface and is independent of the distance from the face (rectilinear scan geometry). For other transducers, such as sector scanners, "scan width" represents the width of the scan on a surface centred at a point, usually within the transducer body. In this case, the "scan width" depends on the distance specified for s_s.

H.1.2 Pulsed wave diagnostic equipment

In all pulsed wave diagnostic equipment, a pulsed waveform is transmitted and either the echo or the transferred signal is analysed.

The acoustic output of pulse-echo diagnostic equipment usually consists of pulses of ultrasound at an **acoustic-working frequency** in the range 1 MHz to 20 MHz, and at **pulse repetition rates** of between 1 kHz and 25 kHz. Pulsed Doppler equipment usually has an acoustic pulse consisting of a number of cycles at **pulse repetition rates** similar to or perhaps higher than pulse-echo equipment. In both types of equipment, the ultrasound is usually focused at distances from the transducer of between a few centimetres and 20 cm, and the **peak acoustic pressure** at the focus is usually between 0,2 MPa and 10 MPa. While linear-array, sector and phased-array scanners emit consecutive pulses along different **ultrasonic scan lines**, the **acoustic pulse waveform** remains approximately constant.

For pulse-echo equipment, the focal diameter is usually less than about 3 mm and, as seen from 5.1.6, a **hydrophone** with an active element of diameter approximately 0,5 mm is needed as well as a relatively precise alignment of the **hydrophone**.

NOTE Some pulse-echo equipment uses unfocused beams in some applications and achieves spatial resolution within the receiving procedures.

As the acoustic pressures are high, the **local distortion parameter** σ_q (see 3.38) will usually be greater than 0,5, in which case the **bandwidth** requirement for the **hydrophone** is greater and additional demands are placed on the angular alignment because of the dependence of this directional response on frequency. Under these conditions, it is important to optimize the rotation of the **hydrophone** to ensure the maximum received signal (see 5.2.2).

In general, diagnostic equipment places the greatest demand on the **hydrophone bandwidth** and on the coordinate positioning system. PVDF **hydrophones** of the membrane or needle type are essential (see Clause B.9). Several investigations have shown the need for broadband **hydrophones** [25], [36], [96], [97].

As measurements for the purpose of determining the maximum output are undertaken in the plane containing the **spatial-peak temporal-peak acoustic pressure**, this plane is expected to be close to the focus of the transducer. At typical focal distances, the square law relationship between acoustic pressure and intensity is usually assumed in order to derive intensity parameters. This assumption is made despite the **uncertainty** associated with the nonlinear distortion that can take place.

H.1.3 Continuous wave diagnostic equipment

Frequencies for continuous wave Doppler systems are usually between 2 MHz and 10 MHz, and an acoustic lens can be used to focus the ultrasound at distances from the transducer face of up to 8 cm. Sometimes the transducer elements have D-shaped crystals, which makes identifying the maxima in any plane complex. **Peak acoustic pressures** are usually less than 0,1 MPa and, consequently, the **local distortion parameter** is generally below 0,5 and a broadband **hydrophone** does not need to be used.

Focal diameters may be less than 3 mm and, as seen from 5.1.6, a **hydrophone** with an active element of diameter 0,5 mm or smaller is needed. For higher frequency devices, it may be necessary to rotate the **hydrophone** when measurements are made at distances from the acoustic axis greater than the transducer radius.

In the case of foetal monitors, the acoustic beam is often divergent, and the **peak acoustic pressure** usually occurs at the face of the **ultrasonic transducer**. Under these circumstances, the usual plane progressive wave approximation for ultrasonic intensity is invalid (see 7.3). Hence, only acoustic pressure parameters can be specified unless a compromise is made. Such a compromise is to undertake measurements in a plane that does not contain the **spatial-peak temporal-peak acoustic pressure** in the whole acoustic field and at a distance such that the plane progressive wave approximation for intensity may be assumed. Although not strictly appropriate for a divergent beam, the criterion given in reference [70] for a plane piston transducer may be used to estimate the difference between the true intensity and the intensity derived from the square of the acoustic pressure. A suitable compromise is to undertake measurements at a distance from the face of the **ultrasonic transducer** of between one and two **ultrasonic transducer element** diameters. For a plane piston transducer, this would yield errors of 4 % and < 2 % for these two cases.

H.2 Therapy fields

H.2.1 Physiotherapy equipment

Ultrasonic transducers used for physiotherapy usually operate between 0,75 MHz and 3 MHz under continuous wave or long tone-burst excitation. IEC 61689 is the related measurement standard. For systems in the frequency range from 20 kHz to 500 kHz, IEC 63009 is the related measurement standard.

Typically, the transducers have active elements of diameter 20 mm and may have an acoustic lens to modify the ultrasonic field. **Peak acoustic pressures** are below 0,5 MPa with no significant nonlinear distortion of the acoustic pressure waveform taking place in the **near field** of the transducer.

General measurements can be made in any plane although it is usual to require them to be made in the **near field**. For measurements made at distances of less than two transducer diameters, there is the same problem of conversion from acoustic pressure to intensity as with the continuous wave Doppler devices (see H.1.3). So, to obtain an absolute value of intensity, it is recommended that measurements are made at distances from the transducer which are greater than or equal to one transducer diameter.

H.2.2 High intensity therapeutic ultrasonic equipment

Specific comments on the measurement of fields generated by high intensity focused ultrasound (HIFU) and high intensity therapeutic ultrasound (HITU) are specified in IEC TS 62556 with respect to measurement at relatively low output levels and methodology for extrapolating these to higher therapeutic level fields.

H.2.3 Non-focused and weakly focused pressure pulses

Specific comments on the measurement of fields generated by non-focusing pressure pulse sources for pain treatment and other applications are specified in IEC 63045.

H.3 Surgical fields

H.3.1 Lithotripters

Specific comments on the measurement of fields generated by pressure pulse lithotripters are specified in IEC 61846.

H.3.2 Low frequency surgical applications

Specific comments on the measurement of fields generated by low frequency surgical systems are specified in IEC 61847.

Annex I
(informative)

Assessment of uncertainty in the acoustic quantities obtained by hydrophone measurements

I.1 General

To be truly meaningful, the result of a measurement should be accompanied by its associated **uncertainty**. 6.4.2 states that, in evaluating and expressing the **uncertainty** in the calibration, the guidance provided by ISO/IEC Guide 98-3:2008 shall be followed.

In general, **uncertainty** components are grouped according to how the values are estimated:

Type A: evaluated by statistical means;

Type B: evaluated by other means.

I.2 Overall (expanded) uncertainty

The overall **uncertainty** should be obtained from all **uncertainty** components in the manner described in ISO/IEC Guide 98-3:2008.

When combining **uncertainty** components, care should be taken when component values are expressed in decibels. Before combination, the values should be expressed in linear form (e.g. as a percentage or in the units of the quantity) and not in logarithmic form. The final value of expanded **uncertainty** may be expressed either in the units of the quantity, as a percentage or converted to decibels as required.

NOTE 1 The use of decibels to express **uncertainties** can lead to asymmetric distributions (e.g. +1,5 dB is equivalent to +19 %, but −1,5 dB is equivalent to −16 %).

NOTE 2 When each component of **uncertainty** is small, i.e. less than 1 dB, the overall **uncertainty** can be calculated using decibels.

I.3 Common sources of uncertainty

The following is a list of common sources of **uncertainty** using **hydrophones**. This list should not be considered exhaustive but may be used as a guide when assessing **uncertainties** for a specific parameter. Depending on the parameter to be measured, some (though possibly not all) of these sources will need assessment. For example, the errors from measuring instruments might be minimized by the use of the same measuring channel (amplifier, filter, voltmeter, etc.) for all signals and measuring only amplitude ratios. However, since this might not be the case in all implementations, components for these sources of error have been included in the list.

Various potential sources of **uncertainty** are as given below.

a) Due to alignment and waterbath:
   1) positioning of the **hydrophone** for maximum signal;
   2) misalignment, particularly at high frequencies where the **hydrophone** response may be far from omnidirectional;
   3) interference from acoustic reflections, leading to a lack of free-field conditions;
   4) acoustic scattering from the **hydrophone** mount (or vibrations picked up and conducted by the mount);
   5) bubbles or air clinging to transducer and or **hydrophone** – this should be minimized by adequate wetting and soaking of transducers and **hydrophones**;

6) cavitation bubbles and dust particles in the water;
7) variation in environmental conditions during the measurements (e.g. temperature, depth, mounting/rigging, etc.);
8) errors in the measurement of distances.

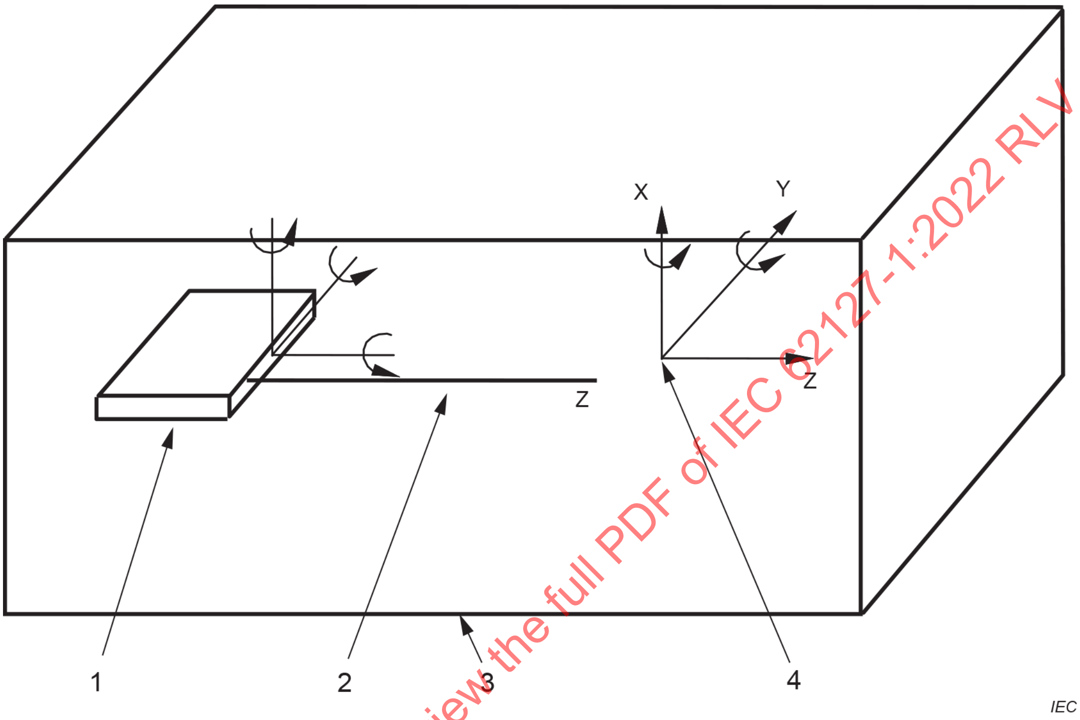
b) Errors related to signal management:
1) **hydrophone** sensitivity data;
2) electrical noise on the **hydrophone** signal include RF pick-up;
3) additional noise through waveform deconvolution (see 5.1.7.2);
4) error due to regularization filtering for deconvolution (see 5.1.7.2.3);
5) inaccuracy of any electrical loading corrections made to account for loading by extension cables and preamplifiers;
6) inaccuracy of any electrical signal attenuators used;
7) errors due to the lack of linearity in the measurement system (the use of a calibrated attenuator to equalize the measured signals may significantly reduce this contribution);
8) inaccuracy of the gains of any amplifiers, filters and digitizers used;
9) errors in measurement of the receive voltage (including the accuracy of the measuring instrumentation – voltmeter, digitizers, etc.);
10) errors due to the resolution of the digitizer;
11) errors in the time base.

c) Errors related to the ultrasonic field:
1) overlapping acoustic scan lines;
2) variation between scan lines;
3) lack of steady-state conditions;
4) errors in the values for acoustic frequency;
5) errors in the values for water density;
6) local temperature variations between repeated measurements;
7) instability of ultrasound transducer (e.g. instability of the output or electrical drive conditions);
8) instability of the **hydrophone**;
9) temperature sensitivity of the **hydrophone**;
10) nonlinear distortion;
11) the spatial averaging effects of the **hydrophones** due to their finite size.

Annex J
(informative)

Transducer and hydrophone positioning systems

There are numerous ways to mount the **ultrasonic transducer** and **hydrophone** such that the requirements specified in 5.2 can be met. Figure J.1 illustrates a possible system.



Key

1 **ultrasonic transducer** (linear array)(translations optional)

2 beam axis

3 tank

4 hydrophone active element

X, Y and Z denote the axis directions relative to the mounted **hydrophone** and **ultrasonic transducer**

Figure J.1 – Schematic diagram of the ultrasonic transducer and hydrophone degrees of freedom

Annex K
(informative)

Beamwidth midpoint method

In the method[5], orthogonal line scans are used and the square root of **pulse-pressure-squared-integral** values, $ppsi$, are divided into 20 intervals corresponding to the −0,1 dB to −26 dB level. See Table K.1.

Beamwidths are calculated at as many of the table decibel levels as signal level will permit, and the locations of their centres are averaged together to obtain **beamwidth midpoints** for both x and y. The intersection of lines perpendicular to scan lines and passing through the midpoints is the **beam centrepoint.**

Table K.1 – Decibel beamwidth levels for determining midpoints

Normalized $\sqrt{ppsi}$ Linear	Normalized $ppsi$ Linear	Levels dB
0,988 5	0,977 1	−0,100 6
0,95	0,902 5	−0,445 5
0,9	0,810 0	−0,915 1
0,85	0,722 5	−1,411 6
0,8	0,640 0	−1,938 2
0,75	0,562 5	−2,498 8
0,7	0,490 0	−3,098 0
0,65	0,422 5	−3,741 7
0,6	0,360 0	−4,437 0
0,55	0,302 5	−5,192 7
0,5	0,250 0	−6,020 6
0,45	0,202 5	−6,935 7
0,4	0,160 0	−7,958 8
0,35	0,122 5	−9,118 6
0,3	0,090 0	−10,457 6
0,25	0,062 5	−12,041 2
0,2	0,040 0	−13,979 4
0,15	0,022 5	−16,478 2
0,1	0,010 0	−20,000 0
0,05	0,002 5	−26,020 6

5 The beamwidth midpoint method is adapted from an approach developed by TNO, Prevention and Health, Leiden, the Netherlands.

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IEC TR 60854, *Methods of measuring the performance of ultrasonic pulse-echo diagnostic equipment*

IEC 61157, *Standard means for the reporting of the acoustic output of medical diagnostic ultrasonic equipment*

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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ULTRASONS – HYDROPHONES –

Partie 1: Mesurage et caractérisation des champs ultrasoniques médicaux

AVANT-PROPOS

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L'IEC 62127-1 a été établie par le comité d'études 87 de l'IEC: Ultrasons. Il s'agit d'une Norme internationale.

Cette deuxième édition annule et remplace la première édition parue en 2007 ainsi que l'Amendement 1:2013. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente.

a) La limite supérieure de fréquence de 40 MHz a été supprimée.
b) Les définitions de la sensibilité des hydrophones ont été modifiées pour considérer les sensibilités comme des grandeurs à valeurs complexes.

c) Les modes opératoires et les exigences concernant l'approximation à bande étroite et les mesurages à large bande ont été modifiés; des informations détaillées sur la déconvolution des formes d'onde ont été ajoutés.

d) Les modes opératoires de correction de la moyenne spatiale ont été modifiés.

e) L'Annexe D, l'Annexe E et la Bibliographie ont été mises à jour pour tenir compte des modifications apportées aux parties normatives.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
87/783/FDIS	87/788/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Le présent document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/standardsdev/publications

Une liste de toutes les parties de la série IEC 62127, publiées sous le titre général *Ultrasons – Hydrophones*, peut être consultée sur le site web de l'IEC.

NOTE Les mots en **gras** dans le texte sont des termes définis à l'Article 3.

Le comité a décidé que le contenu du présent document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous webstore.iec.ch dans les données relatives au document recherché. À cette date, le document sera

- reconduit,
- supprimé,
- remplacé par une édition révisée, ou
- amendé.

INTRODUCTION

Le présent document a pour principal objet de définir différents paramètres acoustiques qui peuvent être utilisés pour préciser et caractériser les champs ultrasoniques qui se propagent dans les liquides et, en particulier, dans l'eau, à l'aide d'hydrophones. Les modes opératoires de mesure présentés peuvent être utilisés pour déterminer ces paramètres. Les normes de mesure liées à des appareils spécifiques (IEC 61689, IEC 61157, IEC 61847 ou IEC 62359, par exemple) peuvent se rapporter au présent document pour des paramètres acoustiques appropriés. Quelques méthodes de mesure supplémentaires des paramètres et indices atténués sont décrites dans l'IEC 62359 pour répondre aux besoins spécifiques de caractérisation des émissions acoustiques des appareils de diagnostic à ultrasons conformément à l'IEC 60601-2-37.

La philosophie sur laquelle repose le présent document porte sur la spécification du champ acoustique en matière de paramètres de pression acoustique, cette dernière étant la principale grandeur de mesure lorsque des hydrophones sont utilisés pour caractériser le champ.

Les paramètres d'intensité sont spécifiés dans le présent document. Cependant, ils sont considérés comme des grandeurs dérivées qui sont significatives uniquement dans le cadre de certaines hypothèses liées au champ ultrasonique mesuré.

ULTRASONS – HYDROPHONES –

Partie 1: Mesurage et caractérisation des champs ultrasoniques médicaux

1 Domaine d'application

La présente partie de l'IEC 62127 spécifie les méthodes d'utilisation des **hydrophones** étalonnés qui permettent de mesurer, dans des liquides, les champs acoustiques générés par des appareils médicaux à ultrasons, y compris les critères de **largeur de bande** et les exigences de plage de fréquences d'étalonnage en fonction du contenu spectral des champs à caractériser.

Le présent document:

- définit un groupe de paramètres acoustiques qui peuvent être mesurés sur une base physiquement sonore;
- définit un second groupe de paramètres qui peuvent être déduits, dans le cadre de certaines hypothèses, de ces mesurages et appelés paramètres d'intensité dérivés;
- définit un mode opératoire de mesure qui peut être utilisé pour déterminer les paramètres de pression acoustique;
- définit les conditions dans lesquelles les mesurages des paramètres acoustiques peuvent être réalisés à l'aide d'**hydrophones** étalonnés;
- définit les modes opératoires de correction, dans le cas de limitations provoquées par l'utilisation d'**hydrophones** à **largeur de bande** finie et de taille d'élément actif finie, ainsi que les modes opératoires d'estimation des **incertitudes** correspondantes.

NOTE 1 Tout au long du présent document, le système international d'unités (SI) est utilisé. Dans la spécification de certains paramètres (les **surfaces du faisceau** ou les intensités, par exemple), il peut être utile d'utiliser des multiples ou sous-multiples décimaux. Par exemple, la **surface du faisceau** est susceptible d'être exprimée en cm^2 et les intensités en W/cm^2 ou mW/cm^2.

NOTE 2 L'**hydrophone**, tel qu'il est défini, peut être de type piézoélectrique ou optique.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60565-1, *Acoustique sous-marine – Hydrophones – Étalonnage des hydrophones – Partie 1: Procédures d'étalonnage en champ libre des hydrophones*

IEC 61689, *Ultrasons – Systèmes de physiothérapie – Spécifications des champs et méthodes de mesure dans la gamme de fréquences de 0,5 MHz à 5 MHz*

IEC 62127-2, *Ultrasons – Hydrophones – Partie 2: Étalonnage des champs ultrasoniques jusqu'à 40 MHz*

IEC 62127-3, *Ultrasons – Hydrophones – Partie 3: Propriétés des hydrophones pour les champs ultrasoniques jusqu'à 40 MHz*

IEC 63009, *Ultrasons – Systèmes de physiothérapie – Spécifications des champs et méthodes de mesure dans la plage de fréquences de 20 kHz à 500 kHz*

ISO 16269-6, *Interprétation statistique des données – Partie 6: Détermination des intervalles statistiques de dispersion*

ISO/IEC Guide 98-3:2008, *Incertitude de mesure – Partie 3: Guide pour l'expression de l'incertitude de mesure (GUM:1995)*

3 Termes et définitions

Pour les besoins du présent document, les termes et définitions de l'IEC 62127-2, de l'IEC 62127-3, ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
forme d'onde des impulsions acoustiques
forme d'onde temporelle de la **pression acoustique instantanée** en une position spécifiée d'un champ acoustique, présentée sur une période suffisamment longue pour inclure toutes les indications acoustiques significatives dans une impulsion, une salve d'impulsions ou un ou plusieurs cycles d'une onde entretenue

Note 1 à l'article: La forme d'onde temporelle est une représentation (par exemple, présentation par oscilloscope ou équation) de la **pression acoustique instantanée**.

3.2
période acoustique de répétition
arp
période de répétition des impulsions des systèmes explorateurs non automatiques et **période de répétition d'exploration** des systèmes explorateurs automatiques, égales à l'intervalle de temps entre les points correspondants des cycles consécutifs des systèmes à ondes entretenues

Note 1 à l'article: La **période acoustique de répétition** est exprimée en secondes (s).

3.3
fréquence d'application acoustique
fréquence acoustique
fréquence d'un signal acoustique fondée sur l'observation de la sortie d'un **hydrophone** placé dans un champ acoustique à la position correspondant à la **pression acoustique à la crête spatiale et temporelle**

Note 1 à l'article: Le signal est analysé à l'aide de la technique de la **fréquence d'application acoustique de passage à zéro** ou de la méthode d'exploration du spectre. Les fréquences d'application acoustique sont définies en 3.3.1, 3.3.2, 3.3.3, 3.3.4 et 3.3.5.

Note 2 à l'article: Dans un certain nombre de cas, la présente définition n'est pas très utile ou pratique, particulièrement pour les **transducteurs à large bande**. Dans ce cas, il est prévu une description complète du spectre de fréquences afin de permettre une correction en fonction de la fréquence par rapport au signal.

Note 3 à l'article: La **fréquence acoustique** est exprimée en hertz (Hz).

3.3.1
fréquence d'application acoustique de passage à zéro
f_{awf}
nombre, n, de demi-périodes consécutives (indépendamment de la polarité) divisé par deux fois le temps qui s'écoule entre le début de la première demi-période et la fin de n-ième demi-période

Note 1 à l'article: Il est prévu qu'aucune des n demi-périodes consécutives ne présente un changement de phase évident.

Note 2 à l'article: Les mesurages sont réalisés, dans le récepteur, aux bornes qui sont le plus proche possible du transducteur de réception (**hydrophone**) et, dans tous les cas, avant redressement.

Note 3 à l'article: Cette fréquence est déterminée conformément à la procédure spécifiée dans l'IEC TR 60854.

Note 4 à l'article: Cette fréquence est destinée aux systèmes à ondes entretenues uniquement.

3.3.2
fréquence d'application acoustique, moyenne arithmétique
f_{awf}
moyenne arithmétique des fréquences les plus largement séparées f_1 et f_2, dans la plage de trois fois f_1, à laquelle le niveau du spectre de la pression acoustique est inférieur de 3 dB au niveau de crête

Note 1 à l'article: Cette fréquence est destinée aux systèmes à ondes pulsées uniquement.

Note 2 à l'article: Par hypothèse $f_1 < f_2$.

Note 3 à l'article: Si f_2 ne se situe pas dans la plage < $3f_1$, f_2, elle doit être considérée comme la fréquence la plus basse au-dessus de cette plage à laquelle le niveau du spectre est de -3 dB du niveau de crête.

3.3.3
fréquence d'application acoustique par amplitude pondérée
f_{awf}
fréquence pondérée avec l'amplitude du spectre de la pression acoustique dans la plage de fréquences dans laquelle le niveau de la pression spectrale est supérieur ou égal à 3 dB en dessous du niveau de crête

$$f_{\text{awf}} = \frac{\int f \left|\underline{P}(f)\right| \mathrm{d}f}{\int \left|\underline{P}(f)\right| \mathrm{d}f} \quad \text{avec} \quad \left|\underline{P}(f)\right| = \begin{cases} \left|\underline{P}(f)\right| & \text{si } L_P(f) \geq \max L_P(f) - 3\,\text{dB} \\ 0 & \text{sinon} \end{cases} \tag{1}$$

où

f est la fréquence du spectre de la pression acoustique;

$|\underline{P}(f)|$ est le module du spectre à valeurs complexes de la **forme d'onde des impulsions acoustiques**;

$L_P(f)$ est le niveau de pression spectral obtenu à partir de $L_P(f) = 20\log_{10}\left(\frac{|\underline{P}(f)|}{P_{\text{ref}}}\right)\text{dB}$ avec P_{ref} = 1 Pa.

Note 1 à l'article: Cette fréquence est destinée aux systèmes à ondes pulsées uniquement.

Note 2 à l'article: Les intégrales dans la formule (1) sont définies, elles sont à prendre en considération du minimum au maximum du spectre du signal acquis.

Note 3 à l'article: La limitation à la plage de niveaux de pression supérieurs ou égaux à -3 dB du niveau de crête doit éviter l'influence des fréquences harmoniques supérieures sur la **fréquence d'application acoustique**.

Note 4 à l'article: La définition 3.3.3 conduit à des résultats de **fréquence d'application acoustique** plus stables que la définition 3.3.2 lorsque des crêtes existent dans le spectre de la pression acoustique proche du seuil de -3 dB. Ceci est particulièrement pertinent pour la détermination des paramètres de champ, de valeur assignée réduite, comme cela est exigé dans l'IEC 62359 en utilisant un seul facteur de réduction de valeur assignée en fonction de la **fréquence d'application acoustique**.

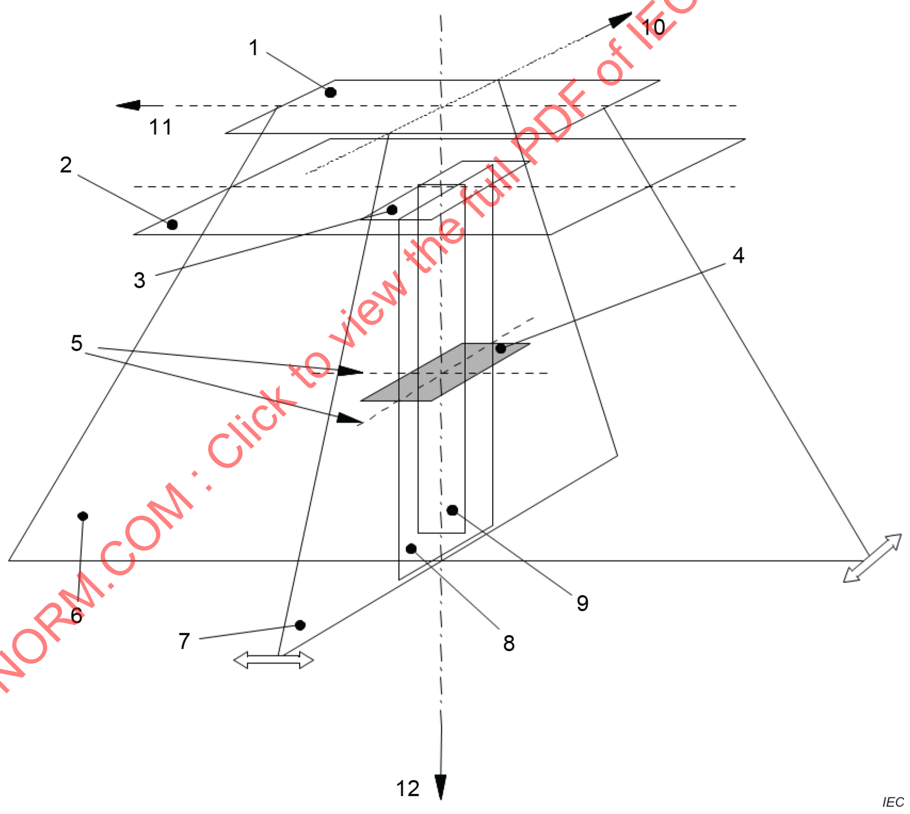
3.3.4
fréquence acoustique d'impulsion de crête
f_p
fréquence d'application acoustique de l'impulsion avec la plus large **pression acoustique négative de crête** mesurée au point de la **pression acoustique négative de crête** maximale

3.3.5
fréquence acoustique à moyenne temporelle
f_t
fréquence d'application acoustique du spectre de pression acoustique de moyenne temporelle des signaux acoustiques mesurée au point de l'**intensité dérivée de la moyenne temporelle** maximale

3.4
axe azimutal
axe formé par l'intersection du **plan azimutal** avec le **plan d'ouverture de la source** (mesurage) ou avec le **plan d'ouverture du transducteur** (conception)

VOIR: Figure 1

[SOURCE: IEC 61828:2020, 3.7]



Légende

1	plan de la surface du transducteur externe	7	plan azimutal, plan d'exploration
2	plan d'ouverture de la source	8	plan longitudinal principal
3	ouverture source	9	plan longitudinal
4	plan de la surface du faisceau	10	X, axe azimutal
5	lignes de largeur de faisceau	11	Y, axe d'élévation
6	plan d'élévation	12	Z, axe du faisceau

[SOURCE: IEC 61828:2020]

Figure 1 – Schéma représentant les différents plans et différentes lignes d'un champ ultrasonique

3.5
plan azimutal
plan contenant l'**axe du faisceau** et la ligne de la **largeur à mi-crête** minimale

VOIR: Figure 1

Note 1 à l'article: Pour un réseau de **transducteurs ultrasoniques**, il s'agit d'un plan d'imagerie.

Note 2 à l'article: Pour un **transducteur ultrasonique** unique à symétrie sphérique ou circulaire, il s'agit de tout plan contenant l'**axe du faisceau**.

[SOURCE: IEC 61828:2020, 3.8]

3.6
largeur de bande
BW
différence dans les fréquences les plus séparées $f1$ et $f2$ à laquelle le niveau du spectre de la pression acoustique devient inférieur à 3 dB au niveau de crête, en un point spécifié du champ acoustique

Note 1 à l'article: La **largeur de bande** est exprimée en hertz (Hz).

3.7
surface du faisceau
$A_{b,6}$, $A_{b,20}$
zone d'un plan particulier perpendiculaire à l'**axe du faisceau** composé de tous les points auxquels l'**intégrale de pression d'impulsion au carré** est supérieure à une fraction spécifiée de la valeur maximale de l'**intégrale de pression d'impulsion au carré** dudit plan

Note 1 à l'article: Si la position du plan n'est pas spécifiée, il s'agit du plan qui passe par le point correspondant à la valeur maximale de l'**intégrale de pression d'impulsion au carré** dans la totalité du champ acoustique.

Note 2 à l'article: Dans un certain nombre de cas, l'expression **intégrale de pression d'impulsion au carré** est remplacée partout dans la définition ci-dessus par une grandeur associée de manière linéaire, par exemple:

a) dans le cas d'un signal à ondes entretenues, l'expression **intégrale de pression d'impulsion au carré** est remplacée par la pression acoustique moyenne au carré telle que définie dans l'IEC 61689,
b) si la synchronisation du signal avec cadre de balayage n'est pas disponible, l'expression **intégrale de pression d'impulsion au carré** peut être remplacée par l'**intensité dérivée de la moyenne temporelle**.

Note 3 à l'article: Certaines fractions spécifiées sont 0,25 et 0,01 pour les surfaces de faisceau −6 dB et −20 dB, respectivement.

Note 4 à l'article: La **surface du faisceau** est exprimée en unités de mètre carré (m^2).

3.8
axe du faisceau
ligne droite qui passe par les **points centraux du faisceau** de deux plans perpendiculaires à la droite associant le point de l'**intégrale de pression d'impulsion au carré** maximum au centre de l'**ouverture du transducteur externe**

VOIR: Figure 1

Note 1 à l'article: L'emplacement du premier plan est celui du plan qui contient l'**intégrale de pression d'impulsion au carré** maximum, ou, alternativement, celui qui contient un seul lobe principal qui se trouve dans la zone Fraunhofer focale. L'emplacement du second plan est, dans la mesure du possible, issu du premier plan et parallèle au premier avec les deux mêmes lignes d'exploration orthogonales (axes x et y) utilisées pour le premier plan.

Note 2 à l'article: Dans un certain nombre de cas, l'expression **intégrale de pression d'impulsion au carré** est remplacée dans la définition ci-dessus par une grandeur associée de manière linéaire, par exemple:

a) dans le cas d'un signal à ondes entretenues, l'expression **intégrale de pression d'impulsion au carré** est remplacée par la pression acoustique moyenne au carré telle que définie dans l'IEC 61689,
b) si la synchronisation du signal avec cadre de balayage n'est pas disponible, l'expression **intégrale de pression d'impulsion au carré** peut être remplacée par l'**intensité dérivée de la moyenne temporelle**.

3.9
point central du faisceau
position déterminée par l'intersection de deux lignes dans le même plan de la surface du faisceau xy passant par les **points médians de largeur de faisceau** des deux plans orthogonaux, xz et yz, perpendiculaires à leurs lignes de largeur de faisceau respectives

[SOURCE: IEC 61828:2020, 3.15, modifiée – Dans la définition, les expressions "dans le même plan de la surface du faisceau xy" et ", perpendiculaires à leurs lignes de largeur de faisceau respectives" ont été ajoutées.]

3.10
point médian de largeur de faisceau
moyenne linéaire de la position des centres de **largeur de faisceau** dans un plan

Note 1 à l'article: La méthode du **point médian de largeur de faisceau** est décrite à l'Annexe K.

Note 2 à l'article: La moyenne est déterminée avec autant de niveaux de **largeur de faisceau** donnés dans le Tableau K.1 que le permet le niveau du signal.

[SOURCE: IEC 61828:2020, 3.22, modifiée – La Note 1 à l'article initiale a été remplacée par de nouvelles Notes à l'article.]

3.11
largeur de faisceau
w_6, w_{12}, w_{20}
distance la plus importante entre deux points d'un axe spécifié perpendiculaire à l'**axe du faisceau**, dans laquelle l'**intégrale de pression d'impulsion au carré** est inférieure à sa valeur maximale sur l'axe spécifié par une quantité donnée

Note 1 à l'article: Dans un certain nombre de cas, l'expression **intégrale de pression d'impulsion au carré** est remplacée dans la définition ci-dessus par une grandeur associée de manière linéaire, par exemple:

a) dans le cas d'un signal à ondes entretenues, l'expression **intégrale de pression d'impulsion au carré** est remplacée par la pression acoustique moyenne au carré telle que définie dans l'IEC 61689,
b) si la synchronisation du signal avec cadre de balayage n'est pas disponible, l'expression **intégrale de pression d'impulsion au carré** peut être remplacée par l'**intensité dérivée de la moyenne temporelle.**

Note 2 à l'article: Les **largeurs de faisceau** communément utilisées sont spécifiées à des niveaux –6 dB, –12 dB et –20 dB en dessous de la valeur maximale. Le calcul de décibel implique l'utilisation de 10 fois le logarithme des rapports des intégrales.

Note 3 à l'article: La **largeur de faisceau** est exprimée en mètres (m).

3.12
transducteur à large bande
transducteur qui génère une impulsion acoustique dont la **largeur de bande** est supérieure à la **fréquence d'application acoustique**

3.13
ligne d'exploration centrale
<pour les systèmes explorateurs automatiques> **ligne d'exploration ultrasonique** la plus proche de l'axe de symétrie du **plan d'exploration**

3.14
intensité instantanée dérivée
quotient de la **pression acoustique instantanée** au carré et impédance acoustique caractéristique du milieu à un instant donné à un point donné d'un champ acoustique

$$I(t) = \frac{p(t)^2}{\rho c} \quad (2)$$

où

$p(t)$ est la **pression acoustique instantanée**;

ρ est la densité du milieu;

c est la vitesse du son dans le milieu

Note 1 à l'article: Pour les besoins des mesurages auxquels fait référence le présent document, l'**intensité instantanée dérivée** est une approximation de l'**intensité instantanée**.

Note 2 à l'article: Il est prévu de prendre en compte l'**incertitude** augmentée pour les mesurages très proches du transducteur.

Note 3 à l'article: L'**intensité instantanée dérivée** est exprimée en unités de watt par mètre carré (W/m^2).

3.15
balayage diamétral de faisceau
ensemble de mesurages de la tension de sortie de l'**hydrophone** réalisés lors du déplacement de l'**hydrophone** dans une ligne droite qui passe par un point de l'**axe du faisceau** et dans une direction perpendiculaire à l'**axe du faisceau**

Note 1 à l'article: Le **balayage diamétral de faisceau** peut être étendu à différentes distances sur l'un ou l'autre des côtés de l'**axe du faisceau**.

3.16
distance z_r

z_r
distance le long de l'**axe du faisceau** entre le plan qui contient la **pression acoustique de raréfaction de crête** et l'**ouverture du transducteur externe**

Note 1 à l'article: La **distance z_r** est exprimée en mètres (m).

3.17
distance z_c

z_c
distance le long de l'**axe du faisceau** entre le plan qui contient la **pression acoustique de compression de crête** et l'**ouverture du transducteur externe**

Note 1 à l'article: La **distance z_c** est exprimée en mètres (m).

3.18
distance z_{ppsi}

z_{ppsi}
distance le long de l'**axe du faisceau** entre le plan qui contient l'**intégrale de pression d'impulsion au carré** maximum et l'**ouverture du transducteur externe**

Note 1 à l'article: La **distance** z_{ppsi} est exprimée en mètres (m).

3.19
distance z_{spta}

z_{spta}
distance le long de l'**axe du faisceau** entre le plan qui contient l'**intensité dérivée de moyenne temporelle de crête spatiale** et l'**ouverture du transducteur externe**

Note 1 à l'article: En pratique, cette distance est égale à celle de z_{ppsi}.

Note 2 à l'article: La **distance** z_{spta} est exprimée en mètres (m).

3.20
taille efficace de l'hydrophone
a_h
dimension d'un **hydrophone** de récepteur théorique qui comporte une fonction de **réponse directionnelle** prévue à angle d'ouverture égal à l'angle d'ouverture observé

Note 1 à l'article: D'une manière générale, la taille dépend de la fréquence. Pour obtenir des données expérimentales représentatives, voir [1].

Note 2 à l'article: La **taille efficace de l'hydrophone** est exprimée en mètres (m).

Note 3 à l'article: Pour les hydrophones de géométrie circulaire, la **taille efficace de l'hydrophone** est un rayon.

Note 4 à l'article: Pour les hydrophones de géométrie rectangulaire, la **taille efficace de l'hydrophone** est la moitié de la valeur la plus élevée de la longueur ou de la largeur.

[SOURCE: IEC 62127-3:2007, 3.2, modifiée – Dans le terme, "rayon" a été remplacé par "taille". Dans la définition, l'expression "rayon d'un hydrophone de récepteur à disque tendu" a été remplacée par "dimension d'un hydrophone de récepteur théorique". Les NOTES ont été remplacées.]

3.21
rayon efficace d'un transducteur ultrasonique sans focalisation
a_t
rayon d'un **transducteur ultrasonique** semblable à un piston à disque parfait qui présente une distribution de la pression acoustique axiale prévue pratiquement équivalente à celle observée sur une distance axiale tant que le dernier maximum axial au moins n'est pas passé

Note 1 à l'article: Le **rayon efficace d'un transducteur ultrasonique sans focalisation** est exprimé en mètres (m).

3.22
impédance de charge électrique
$\underline{Z}_L$
impédance d'entrée électrique complexe (composée d'une partie réelle et d'une partie imaginaire) à laquelle le câble de sortie de l'**hydrophone** est ou est destiné à être connecté

Note 1 à l'article: L'**impédance de charge électrique** est exprimée en ohms (Ω).

[SOURCE: IEC 62127-3:2007, 3.3, modifiée – Dans la définition, "la sortie de l'**hydrophone** ou de l'**ensemble d'hydrophones** est connectée ou convient d'être connectée" a été remplacé par "le câble de sortie de l'**hydrophone** est ou est destiné à être connecté".]

3.23
axe d'élévation
droite comprise dans le **plan d'ouverture de la source** (mesurage) ou dans le **plan d'ouverture du transducteur** (conception) et perpendiculaire à l'**axe azimutal** et à l'**axe du faisceau**

VOIR: Figure 1

[SOURCE: IEC 61828:2020, 3.48 modifiée – Les Notes à l'article initiales ont été omises.]

3.24
plan d'élévation
plan longitudinal contenant l'**axe d'élévation**

VOIR: Figure 1

[SOURCE: IEC 61828:2020, 3.49, modifiée – Les mots "et l'axe du faisceau" ont été supprimés puisqu'ils sont déjà compris dans la définition de plan longitudinal.]

3.25
sensibilité en bout de câble
$\underline{M}_L(f)$
<d'un **hydrophone** ou d'un **ensemble d'hydrophones**> quotient de la transformée de Fourier du signal tension-temps de l'**hydrophone** $\mathcal{F}(u_L(t))$ à l'extrémité de tout câble intégré ou connecteur de sortie d'un **hydrophone** ou d'un **ensemble d'hydrophones**, lorsqu'il est connecté à une **impédance de charge électrique** spécifiée, et de la transformée de Fourier $\mathcal{F}(p(t))$ de la **forme d'onde des impulsions acoustiques** dans le champ libre non perturbé d'une onde plane à la position du **centre de référence** de l'**hydrophone** si l'**hydrophone** a été retiré

$$\underline{M}_L(f) = \frac{\mathcal{F}(u_L(t))}{\mathcal{F}(p(t))} \tag{3}$$

Note 1 à l'article: La **sensibilité en bout de câble** est un paramètre à valeurs complexes. Son module est exprimé en unités de volts par pascal (V/Pa). Son angle de phase est exprimé en degrés et représente la différence de phase entre la tension électrique et la pression acoustique.

3.26
niveau de sensibilité en bout de câble
$L_{M_L}(f)$
<d'un **hydrophone** ou d'un **ensemble d'hydrophones**> vingt fois le logarithme en base 10 du quotient du module de la **sensibilité en bout de câble** $|\underline{M}_L(f)|$ et d'une sensibilité de référence M_{ref}

$$L_{M_L}(f) = 20\log_{10}\frac{|\underline{M}_L(f)|}{M_{ref}}\,\text{dB} \tag{4}$$

Note 1 à l'article: Les valeurs couramment utilisées de la sensibilité de référence M_{ref} sont 1 V/µPa ou 1 V/Pa.

Note 2 à l'article: Le **niveau de sensibilité en bout de câble** est exprimé en décibels (dB).

3.27
sensibilité en circuit ouvert en bout de câble
$\underline{M}_c(f)$
<d'un **hydrophone**> quotient de la transformée de Fourier du signal tension-temps en circuit ouvert de l'**hydrophone** $\mathcal{F}(u_c(t))$ à l'extrémité de tout câble intégré ou connecteur de sortie d'un **hydrophone** et de la transformée de Fourier $\mathcal{F}(p(t))$ de la **forme d'onde des impulsions acoustiques** dans le champ libre non perturbé d'une onde plane à la position du **centre de référence** de l'**hydrophone** si l'**hydrophone** a été retiré

$$\underline{M}_c(f) = \frac{\mathcal{F}(u_c(t))}{\mathcal{F}(p(t))} \tag{5}$$

Note 1 à l'article: La **sensibilité en circuit-ouvert en bout de câble** est un paramètre à valeurs complexes. Son module est exprimé en unités de volts par pascal (V/Pa). Son angle de phase est exprimé en degrés et représente la différence de phase entre la tension électrique et la pression acoustique.

3.28
surface du transducteur externe
ouverture du transducteur externe
partie de la surface d'un **transducteur ultrasonique** ou d'un **groupe d'éléments transducteurs ultrasoniques** émettant un rayonnement ultrasonore dans le milieu de propagation

VOIR: Figure 1

Note 1 à l'article: Cette surface est réputée accessible pour procéder aux mesurages à l'aide d'un hydrophone dans le milieu de propagation choisi (en général, de l'eau).

Note 2 à l'article: Cette surface est en contact direct avec le patient ou avec un chemin constitué d'eau ou de liquide menant au patient.

[SOURCE: IEC 61828:2020, 3.52]

3.29
plan de la surface du transducteur externe
plan de l'ouverture du transducteur externe
plan orthogonal à l'**axe du faisceau** non défléchi ou à l'axe de symétrie du **plan azimutal** d'un scanneur automatique, et physiquement adjacent au **transducteur ultrasonique** et à la **surface du transducteur externe**

VOIR: Figure 2

Note 1 à l'article: Si le **transducteur ultrasonique** est plat, le plan est coplanaire avec la surface de rayonnement du **transducteur ultrasonique**. S'il est concave, le plan touche la périphérie de la surface de rayonnement. S'il est convexe, le plan est tangent au centre de la surface de rayonnement au point de contact.

[SOURCE: IEC 61828:2020, 3.53]

3.30
champ lointain
région du champ dans laquelle $z > z_T$ est alignée sur l'**axe de faisceau** pour des transducteurs plans sans focalisation

Note 1 à l'article: Dans le **champ lointain**, la pression acoustique apparaît comme sphériquement divergente depuis un point situé sur ou à proximité de la surface rayonnante. Ainsi, la pression produite par la source acoustique est à peu près inversement proportionnelle à la distance depuis la source.

Note 2 à l'article: Le terme "**champ lointain**" est utilisé dans le présent document uniquement dans le cas de transducteurs sans focalisation. Pour les transducteurs à focalisation, une terminologie différente s'applique aux différentes parties du champ émis (voir IEC 61828).

Note 3 à l'article: Si la forme de l'ouverture du transducteur génère plusieurs **distances de transition**, la distance la plus éloignée du transducteur est utilisée.

3.31
rayon géométrique de l'hydrophone
a_g
rayon défini par les dimensions de l'élément actif d'un **hydrophone**

Note 1 à l'article: Le **rayon géométrique de l'hydrophone** est exprimé en mètres (m).

[SOURCE: IEC 62127-3:2007, 3.8]

3.32
hydrophone
transducteur qui produit des signaux électriques en réponse aux variations de pression dans l'eau

Note 1 à l'article: Il s'agit principalement d'un dispositif passif conçu et fabriqué pour répondre à la pression acoustique.

Note 2 à l'article: Dans certaines applications, il sert de dispositif actif pour l'émission du son.

[SOURCE:IEC 60050-801:2021, 801-32-26]

3.33
ensemble d'hydrophones
combinaison d'un **hydrophone** et d'un **préamplificateur d'hydrophone**

[SOURCE: IEC 62127-3:2007, 3.10]

3.34
préamplificateur de l'hydrophone
dispositif électronique actif connecté ou à connecter à un **hydrophone** particulier et permettant de réduire son impédance de sortie

Note 1 à l'article: Le **préamplificateur de l'hydrophone** requiert une/des tension(s) d'alimentation.

Note 2 à l'article: Le **préamplificateur de l'hydrophone** peut faire l'objet d'un facteur de transmission de la tension directe inférieur à un, c'est-à-dire qu'il ne s'agit pas nécessairement d'un amplificateur de tension stricto sensu.

[SOURCE: IEC 62127-3:2007, 3.12]

3.35
pression acoustique instantanée
$p(t)$
pression à un instant et un point donnés dans un champ acoustique, diminuée de la pression ambiante

Note 1 à l'article: La **pression acoustique instantanée** est exprimée en pascals (Pa).

[SOURCE: IEC 60050-802:2011, 802-01-03]

3.36
intensité instantanée
$I(t)$
énergie acoustique transmise par unité de temps dans la direction de propagation de l'onde acoustique par unité de masse perpendiculaire à cette direction à un instant et un point donnés dans un champ acoustique

Note 1 à l'article: L'**intensité instantanée** est le produit de la **pression acoustique instantanée** et de la vitesse acoustique. Il est difficile de mesurer l'intensité dans la plage de fréquences ultrasoniques. Pour les besoins des mesurages auxquels fait référence le présent document et dans des conditions de distance suffisante de l'**ouverture du transducteur externe** (au moins un diamètre de transducteur ou une dimension de transducteur équivalente dans le cas d'un transducteur non circulaire), l'**intensité instantanée** peut être approchée par l'**intensité instantanée dérivée**.

Note 2 à l'article: L'**intensité instantanée** est exprimée en unités de watt par mètre carré (W/m^2).

3.37
facteur de surface locale
F_a
racine carrée du quotient de la **surface d'ouverture de la source** sur la **surface du faisceau** au point considéré

$$F_a = \sqrt{\frac{A_{SAeff}}{A_b}} \quad (6)$$

Note 1 à l'article: La **surface** locale **du faisceau** correspondante, A_b, est celle pour laquelle la valeur de l'**intégrale de pression d'impulsion au carré** est supérieure à 0,135 (c'est-à-dire, 1/e^2) fois la valeur maximale dans la section.

Note 2 à l'article: Si le profil du faisceau est approximativement gaussien à la distance à l'étude et si la surface du faisceau au niveau de -6 dB, $A_{b,6}$, est connue, la **surface** locale du **faisceau** peut être calculée sous la forme $A_b = A_{b,6}/0,69$: (0,69 = 3 ln(10)/10): $F_a = \sqrt{\frac{0,69 A_{SAeff}}{A_{b,6}}}$.

[SOURCE: IEC TS 61949:2007, 3.11 modifiée – "ouverture source" a été remplacée par "surface d'ouverture de la source"; la formule du cas général a été ajoutée; la deuxième phrase de la définition originale a été déplacée en Note 1 à l'article; la troisième phrase de la définition originale a été transformée en Note 2 à l'article et fournit plus de précisions et le symbole de la **surface du faisceau** à -6 dB a été modifié pour être conforme à l'Article 4.]

3.38
paramètre de déformation locale
σ_q
indice permettant de prévoir la déformation non linéaire d'un ultrason pour un **transducteur ultrasonique**

$$\sigma_q = z\, p_m \frac{2\pi f_{awf}\, \beta}{\rho \cdot c^3} \frac{1}{\sqrt{F_a}} \tag{7}$$

où

z est la distance axiale du point pris en considération à la face du transducteur;

p_m est la **pression acoustique de crête moyenne** au point du champ acoustique correspondant à la **pression acoustique à la crête spatiale et temporelle**;

β est le paramètre non linéaire (β = 1 + $B/2A$ = 3,5 pour l'eau douce à 20 °C);

f_{awf} est la **fréquence d'application acoustique**;

F_a est le **facteur de surface locale**.

Note 1 à l'article: Si le système d'émission comprend une colonne interne qui utilise un milieu de propagation à base d'eau ou équivalent à l'eau, la distance de décalage entre l'élément transducteur et la face du transducteur augmente la longueur réelle du trajet z à prendre en considération. La distance nominale entre l'intersection de l'**axe du faisceau** avec le cristal et la face du transducteur peut être utilisée.

[SOURCE: IEC TS 61949:2007, 3.12, modifiée – Le texte de la définition a été modifié considérablement, toutefois la formule reste inchangée; la Note 1 à l'article a été ajoutée.]

3.39
plan longitudinal
plan défini par l'**axe du faisceau** et un axe orthogonal spécifié

VOIR: Figure 1

3.40
pression acoustique de crête moyenne
p_m
moyenne arithmétique de la **pression acoustique de raréfaction de crête** et de la **pression acoustique de compression de crête**

Note 1 à l'article: La **pression acoustique de crête moyenne** est exprimée en pascals (Pa).

[SOURCE: IEC TS 61949:2007, 3.13, modifiée – La Note 1 à l'article a été ajoutée.]

3.41
champ proche
région du champ dans laquelle $z < z_T$ est alignée sur l'**axe de faisceau** pour des transducteurs plans sans focalisation

Note 1 à l'article: Dans le cas des transducteurs circulaires plans, il se trouve à une distance inférieure à $A_{ob}/\pi\lambda$, où A_{ob} est la **surface du faisceau de sortie** et λ la longueur d'onde de l'ultrason qui correspond à la **fréquence acoustique**.

Note 2 à l'article: Si la forme de l'ouverture du transducteur génère plusieurs **distances de transition**, la distance la plus proche du transducteur est utilisée.

3.42
nombre d'impulsions par ligne d'exploration ultrasonique
n_{pps}
nombre d'impulsions acoustiques se propageant le long d'une **ligne d'exploration ultrasonique** particulière

Note 1 à l'article: Ici la **ligne d'exploration ultrasonique** se réfère au parcours des impulsions acoustiques sur un **axe du faisceau** particulier en **modes explorateurs** et non **explorateurs**.

Note 2 à l'article: Ce nombre peut être utilisé dans le calcul de toute valeur moyenne temporelle des ultrasons par des mesures de l'**hydrophone**.

Note 3 à l'article: L'exemple suivant représente le **nombre d'impulsions par ligne d'exploration ultrasonique** et le **nombre de lignes d'exploration ultrasoniques** (représente la fin de la salve):

1 2 3 4; 1 2 3 4; 1 2 3 4… n_{pps} =1; n_{sl} = 4
1 1 2 2 3 3 4 4; 1 1 2 2 3 3 4 4; … n_{pps} = 2; n_{sl} = 4
1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4; 1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4; … n_{pps} = 4; n_{sl} = 4
1 1 2 2 3 3 4 4 1 1 1 2 2 2 3 3 3 4 4 4; 1 1 2 2 3 3 4 4 1 1 1 2 2 2 3 3 3 4 4 4; … n_{pps} = 5; n_{sl} = 4 (dans une salve, les impulsions descendent à chaque ligne sans être contigües)

Note 4 à l'article: Dans une salve, toutes les lignes d'exploration n'ont peut-être pas la même valeur n_{pps}.
Par exemple: 1 2 2 3 3 4; 1 2 2 3 3 4; … avg n_{pps} = 1,5; max n_{pps} = 2; n_{sl} = 4

[SOURCE: IEC 61157:2007/AMD1:2013, 3.45 modifiée – Le quatrième exemple de la Note 3 à l'article a été corrigé et le dernier exemple a été transformé en Note 4 à l'article.]

3.43
nombre de lignes d'exploration ultrasonique
n_{sl}
quantité de **lignes d'exploration ultrasonique** excitées pendant une **période de répétition d'exploration**

Note 1 à l'article: Ce nombre peut être utilisé dans le calcul des valeurs moyennes temporelles des **modes explorateurs** par des mesurages de l'**hydrophone**.

[SOURCE: IEC 61157:2007/AMD1:2013, 3.46]

3.44
distance de décalage
d_{offset}
distance entre le **plan d'ouverture de la source** et le **plan de la surface du transducteur externe**, mesurée le long de l'**axe du faisceau**

VOIR: Figure 2

Note 1 à l'article: La **distance de décalage** est exprimée en mètres (m).

[SOURCE: IEC 61828:2020, 3.90]

3.45
mode opératoire
mode de fonctionnement d'un **système**

3.45.1
mode opératoire combiné
mode opératoire qui combine plusieurs **modes opératoires discrets**

Note 1 à l'article: Le mode B en temps réel combiné avec mode M (B+M), le mode B en temps réel combiné avec Doppler pulsé (B+D), le mode M couleur (cM), le mode B en temps réel combiné avec mode M et Doppler pulsé (B+M+D), le mode B en temps réel combiné avec Doppler à traçage de déroulement en temps réel (B+rD), c'est-à-dire le traçage de déroulement dans lequel différents types d'impulsions acoustiques sont utilisés pour produire l'information Doppler et l'information de composition d'image, sont autant d'exemples de **modes opératoires combinés.**

3.45.2
mode opératoire discret
mode opératoire des **appareils de diagnostic médical à ultrasons** dans lequel l'objectif de l'excitation du **transducteur ultrasonique** ou du **groupe d'éléments transducteurs ultrasoniques** est d'appliquer seulement une méthodologie de diagnostic

Note 1 à l'article: Le mode A (A), le mode M (M), le mode B statique (sB), le mode B en temps réel (B), le Doppler à ondes entretenues (cwD), le Doppler pulsé (D), le traçage de déroulement statique (sD) et le Doppler à traçage de déroulement en temps réel (rD) qui utilise seulement un type d'impulsion acoustique sont autant d'exemples de **modes opératoires discrets.**

3.45.3
mode inclusif
mode opératoire combiné dont les niveaux de puissance acoustique (p_r et I_{spta}) sont inférieurs à ceux qui correspondent à un **mode opératoire discret**

3.45.4
mode non explorateur
mode opératoire qui implique une séquence d'impulsions ultrasoniques donnant lieu à des **lignes d'exploration ultrasonique** qui suivent le même parcours acoustique

3.45.5
mode explorateur
mode opératoire qui implique une séquence d'impulsions ultrasoniques donnant lieu à des **lignes d'exploration ultrasonique** qui ne suivent pas le même parcours acoustique

3.46
surface du faisceau de sortie
A_{ob}
surface du faisceau acoustique dérivée de la **surface du faisceau** à −12 dB au niveau de l'**ouverture du transducteur externe**

Note 1 à l'article: Pour des raisons d'exactitude de mesure, la **surface du faisceau de sortie** à –12 dB découle de mesurages réalisés à une distance aussi proche que possible de la face du transducteur et, dans la mesure du possible, pas plus de 1 mm de la face.

Note 2 à l'article: Pour les transducteurs à contact, cette surface peut être prise comme la surface géométrique du **transducteur ultrasonique** ou d'un **groupe d'éléments transducteurs ultrasoniques**.

Note 3 à l'article: La **surface du faisceau de sortie** est exprimée en unités de mètre carré (m^2).

3.47
dimensions du faisceau de sortie
X_{ob}, Y_{ob}
dimensions du faisceau acoustique (**largeur de faisceau**–12 dB) dans les directions spécifiées perpendiculaires l'une par rapport à l'autre et perpendiculaire à l'**axe du faisceau** et à l'**ouverture du transducteur externe**

Note 1 à l'article: Pour des raisons d'exactitude de mesure, les **dimensions du faisceau de sortie** à –12 dB découlent de mesurages réalisés à une distance aussi proche que possible de la face du transducteur et, dans la mesure du possible, pas plus de 1 mm de la face.

Note 2 à l'article: Pour les transducteurs à contact, ces dimensions peuvent être prises comme les dimensions géométriques du **transducteur ultrasonique** ou d'un **groupe d'éléments transducteurs ultrasoniques**.

Note 3 à l'article: Les **dimensions du faisceau de sortie** sont exprimées en mètres (m).

3.48
intensité du faisceau de sortie
I_{ob}
sortie d'énergie moyenne temporelle divisée par la **surface du faisceau de sortie**

Note 1 à l'article: L'**intensité du faisceau de sortie** est exprimée en unités de watt par mètre carré (W/m^2).

3.49
pression acoustique de crête
p_{c} (ou p_+) ou p_{r} (ou p_-)
pression acoustique de compression de crête ou **pression acoustique de raréfaction de crête**

Note 1 à l'article: La **pression acoustique de crête** est exprimée en pascals (Pa).

3.50
pression acoustique de compression de crête
p_{c} (ou p_+)
pression acoustique instantanée positive maximale dans un champ acoustique ou un plan spécifié lors d'une **période acoustique de répétition**

Note 1 à l'article: La **pression acoustique de compression de crête** est exprimée en pascals (Pa).

Note 2 à l'article: La définition de la **pression acoustique de compression de crête** s'applique également à la pression acoustique positive de crête utilisée dans tous les ouvrages de référence.

3.51
pression acoustique de raréfaction de crête
p_{r} (ou p_-)
maximum du module de la **pression acoustique instantanée** négative dans un champ acoustique ou dans un plan spécifié pendant la **période acoustique de répétition**

Note 1 à l'article: La **pression acoustique de raréfaction de crête** est exprimée en utilisant un nombre positif pour la valeur numérique.

Note 2 à l'article: La **pression acoustique de raréfaction de crête** est exprimée en pascals (Pa).

Note 3 à l'article: La définition de la **pression acoustique de raréfaction de crête** s'applique également à la pression acoustique négative de crête utilisée dans tous les ouvrages de référence.

3.52
plan longitudinal principal
plan contenant l'**axe du faisceau** et deux points qui définissent la **largeur de faisceau** −6 dB minimale

VOIR: Figure 1

Note 1 à l'article: Le choix de cet axe est arbitraire pour un transducteur à symétrie circulaire.

Note 2 à l'article: En présence d'un trou au centre d'un transducteur HITU, dans lequel se trouve un transducteur d'imagerie de diagnostic, cet axe est aligné sur l'axe azimutal du transducteur d'imagerie.

Note 3 à l'article: Pour les **transducteurs ultrasoniques** rectangulaires, il s'agit du plan parallèle à leur côté le plus long.

[SOURCE: IEC 61828:2020, 3.110 modifiée – La référence au transducteur HITU a été supprimée de la Note 1 à l’article.]

3.53
intensité moyenne de l'impulsion
I_{pa}
quotient de l'**intégrale d'intensité d'impulsion** sur la **durée d'impulsion** en un point particulier d'un champ acoustique

Note 1 à l’article: Cette définition concerne les impulsions et les salves.

Note 2 à l’article: L'**intensité moyenne de l’impulsion** est exprimée en unités de watt par mètre carré (W/m^2).

3.54
durée d’impulsion
t_d
1,25 fois l'intervalle entre l'instant auquel l'intégrale de temps du carré de la **pression acoustique instantanée** atteint 10 % et 90 % de sa valeur finale

VOIR: Figure 4

Note 1 à l’article: La valeur finale de l'intégrale de temps du carré de la **pression acoustique instantanée** est l'**intégrale de pression d'impulsion au carré**.

Note 2 à l’article: La **durée d’impulsion** est exprimée en secondes (s).

3.55
intégrale d'intensité d'impulsion
pii
intégrale de temps de l'**intensité instantanée** en un point particulier d'un champ acoustique intégré à la **forme d'onde des impulsions acoustique**

Note 1 à l’article: Pour les besoins des mesurages auxquels fait référence le présent document, l'**intégrale d'intensité d'impulsion** est proportionnelle à l'**intégrale de pression d'impulsion au carré**.

Note 2 à l’article: L’**intégrale d'intensité d'impulsion** est exprimée en unités de joule par mètre carré (J/m^2).

3.56
intégrale de pression d'impulsion au carré
ppsi
intégrale de temps du carré de la **pression acoustique instantanée** à un point particulier dans un champ acoustique intégré sur la **forme d'onde des impulsions acoustique**

Note 1 à l’article: L’**intégrale de pression d'impulsion au carré** est exprimée en unités de pascal au carré secondes (Pa^{2}s).

3.57
période de répétition des impulsions
prp
intervalle de temps entre deux impulsions successives ou giclées de tonalité d’impulsions qui comprend un **mode opératoire discret**

Note 1 à l’article: La **période de répétition des impulsions** est exprimée en secondes (s).

3.58
régime de répétition des impulsions
prr
inverse de la **période de répétition des impulsions**

Note 1 à l’article: Le **régime de répétition des impulsions** est exprimé en hertz (Hz).

3.59
centre de référence
<d'un **hydrophone**> point situé sur, à l'intérieur ou au voisinage d'un **hydrophone**, autour duquel ses caractéristiques électro-acoustiques sont définies

Note 1 à l'article: Sauf indication contraire, le **centre de référence** correspond souvent au centre géométrique d'un élément actif de l'**hydrophone**.

[SOURCE: IEC 60500:2017, 3.26, modifiée – Le contexte <d'un **hydrophone**> et le terme "élément actif" dans la Note 1 à l'article ont été ajoutés. Dans la définition, le mot "géométriques" a été supprimé.]

3.60
pression acoustique efficace
p_{RMS}
valeur efficace de la **pression acoustique instantanée** en un point donné du champ acoustique

Note 1 à l'article: Sauf spécification contraire, il convient de prendre la moyenne sur un nombre entier de **périodes acoustiques de répétition**.

Note 2 à l'article: La **pression acoustique efficace** est exprimée en pascals (Pa).

3.61
surface d'exploration
A_{s}
<pour les systèmes explorateurs automatiques> surface d'un plan (ou d'une surface) spécifié(e) composée de tous les points de la **surface du faisceau** qui passent par la surface au cours de l'exploration

Note 1 à l'article: La forme du plan (ou de la surface) spécifié(e) est identique à celle de l'**ouverture du transducteur externe**.

Note 2 à l'article: La **surface d'exploration** est exprimée en unités de mètre carré (m^2).

3.62
plan d'exploration
<pour les systèmes explorateurs automatiques> plan qui contient toutes les **lignes d'exploration ultrasonique**

Note 1 à l'article: Certains systèmes explorateurs offrent la possibilité d'orienter le faisceau ultrasonique dans deux directions. Dans ce cas, aucun **plan d'exploration** ne satisfait à cette définition. Néanmoins, il peut être utile de considérer qu'un plan qui passe par le grand axe de symétrie du **transducteur ultrasonique** et perpendiculaire à la face du transducteur (ou à un autre plan adapté) est équivalent au **plan d'exploration**.

3.63
période de répétition des explorations
srp
<pour les systèmes explorateurs automatiques à séquence périodique d'exploration> intervalle de temps entre des points identiques sur deux explorations, secteurs ou images successifs

Note 1 à l'article: En général, le présent document part du principe qu'une ligne d'exploration se répète exactement après un certain nombre d'impulsions acoustiques. Si un **transducteur ultrasonique** ou un **groupe d'éléments transducteurs ultrasoniques** émet des ultrasons sans séquence de répétition, il n'est pas possible de caractériser un mode explorateur de la manière décrite dans le présent document. L'approche décrite à l'Annexe F peut être utile lorsque la synchronisation ne peut être obtenue.

Note 2 à l'article: La **période de répétition des explorations** est exprimée en secondes (s).

3.64
régime de répétition des explorations
srr
inverse de la **période de répétition des explorations**

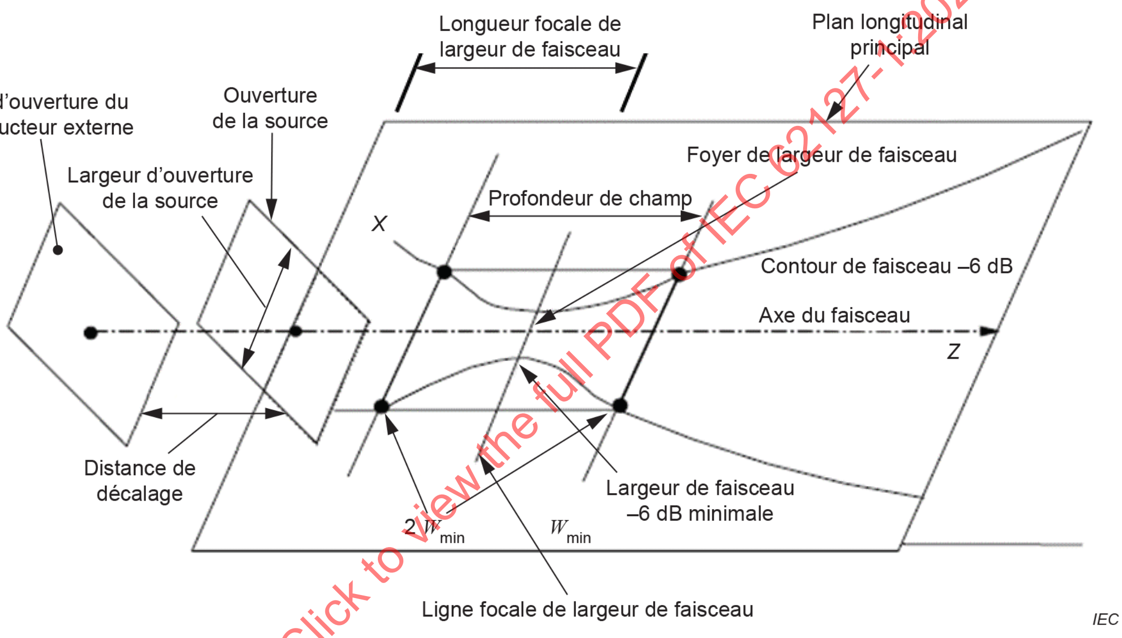
Note 1 à l'article: Le **régime de répétition des explorations** est exprimé en hertz (Hz).

3.65
surface d'ouverture de la source A_{SAeff}
surface d'ouverture équivalente pour un **transducteur ultrasonique** de caractéristiques inconnues, mesurée comme la surface dans le contour de l'**intégrale de pression d'impulsion au carré** à –20 dB dans le plan de mesure le plus proche possible (plan d''ouverture de la source) de l'**ouverture du transducteur externe**

VOIR: Figure 2

Note 1 à l'article: La surface nominale d'émission de la source peut être utilisée pour calculer le **paramètre de déformation locale** σ_q lorsqu'il existe un décalage significatif entre le cristal du transducteur et la face avant en raison d'une colonne interne.

Note 2 à l'article: La **surface d'ouverture de la source** est exprimée en unités de mètre carré (m^2).



[SOURCE: IEC 61828:2020]

Figure 2 – Ouvertures et plans différents pour un transducteur de géométrie inconnue

3.66
plan d'ouverture de la source
plan de mesurage le plus proche possible du **plan de la surface du transducteur externe** et perpendiculaire à l'**axe du faisceau**

VOIR: Figure 2

Note 1 à l'article: Si la **distance de décalage** est nulle, le **plan d'ouverture de la source** peut coïncider avec le **plan d'ouverture du transducteur externe**.

[SOURCE: IEC 61828:2020, 3.135]

3.67
largeur d'ouverture source
L_{SA}
<dans un **plan longitudinal** spécifié> plus grande **largeur de faisceau** –20 dB le long de la ligne d'intersection entre le **plan longitudinal** désigné et le **plan d'ouverture de la source**

VOIR: Figure 2

Note 1 à l'article: S'il s'agit d'un transducteur à symétrie circulaire, un balayage de ligne radial est suffisant pour déterminer la largeur.

Note 2 à l'article: Si le transducteur HITU comporte un trou en son centre, le début et la fin des points −20 dB de la largeur sont mesurés et notés par rapport au centre.

Note 3 à l'article: La **largeur d'ouverture source** est exprimée en mètres (m).

[SOURCE: IEC 61828: 2020, 2020, 3.136 modifiée – La référence au transducteur HITU a été supprimée de la Note 1 à l'article.]

3.68
intensité moyenne de l'impulsion de moyenne spatiale
I_{sapa}
intensité moyenne de l'impulsion d'un **transducteur ultrasonique** ou **groupe d'éléments transducteurs ultrasoniques** moyennée sur la **surface du faisceau** pour le **transducteur ultrasonique** ou le **groupe d'éléments transducteurs ultrasoniques** particulier

Note 1 à l'article: Une salve est également considérée comme une impulsion.

Note 2 à l'article: L'**intensité moyenne de l'impulsion de moyenne spatiale** est exprimée en unités de watt par mètre carré (W/m^2).

3.69
intensité dérivée de moyenne temporelle de moyenne spatiale
I_{sata}
égale à l'**intensité dérivée de moyenne temporelle** obtenue par calcul de la moyenne sur la **surface d'exploration** ou la **surface du faisceau**, selon le cas

Note 1 à l'article: L'**intensité dérivée de moyenne temporelle de moyenne spatiale** est exprimée en unités de watt par mètre carré (W/m^2).

3.70
intensité dérivée de la moyenne d'impulsions de crête spatiale
I_{sppa}
valeur maximale de l'**intensité dérivée de la moyenne d'impulsions** dans un champ acoustique ou dans un plan spécifié

Note 1 à l'article: L'**intensité dérivée de la moyenne d'impulsions de crête spatiale** est exprimée en unités de watt par mètre carré (W/m^2).

3.71
pression acoustique efficace à la crête spatiale
p_{spr}
valeur maximale de la **pression acoustique efficace** dans un champ acoustique ou dans un plan spécifié

Note 1 à l'article: La **pression acoustique efficace à la crête spatiale** est exprimée en pascals (Pa).

3.72
intensité dérivée de moyenne temporelle de crête spatiale
I_{spta}
valeur maximale de l'**intensité dérivée de la moyenne temporelle** dans un champ acoustique ou dans un plan spécifié

Note 1 à l'article: Pour les systèmes en **mode opératoire combiné**, l'intervalle de temps sur lequel la moyenne temporelle est suffisante pour inclure toute période pendant laquelle l'exploration n'a pas lieu.

Note 2 à l'article: L'**intensité dérivée de moyenne temporelle de crête spatiale** est exprimée en unités de watt par mètre carré (W/m^2).

3.73
pression acoustique à la crête spatiale et temporelle
p_{sptp}
valeur supérieure de la **pression acoustique de compression de crête** et de la **pression acoustique de raréfaction de crête**

Note 1 à l'article: La **pression acoustique à la crête spatiale et temporelle** est exprimée en pascals (Pa).

3.74
intensité à la crête spatiale et temporelle
I_{sptp}
valeur maximale de l'**intensité à la crête temporelle** dans un champ acoustique ou dans un plan spécifié

Note 1 à l'article: L'**intensité à la crête spatiale et temporelle** est exprimée en unités de watt par mètre carré (W/m^2).

3.75
intensité dérivée de la moyenne temporelle
I_{ta}
moyenne temporelle de l'**intensité instantanée** en un point particulier dans un champ acoustique

Note 1 à l'article: La moyenne temporelle est prise sur un nombre entier de **périodes acoustiques de répétition**.

Note 2 à l'article: En principe, l'**intensité dérivée de la moyenne temporelle** est une moyenne temporelle calculée sur un intervalle de temps relativement long. Pour les appareils de diagnostic médical à ultrasons en **modes non explorateurs**, la moyenne de l'**intensité instantanée** est calculée sur une ou plusieurs **périodes de répétition des impulsions**. Pour les appareils de diagnostic médical à ultrasons en **modes explorateurs**, la moyenne de l'**intensité instantanée** est calculée sur une ou plusieurs **périodes de répétition d'exploration** pour un **mode opératoire** spécifié.

Note 3 à l'article: L'**intensité dérivée de la moyenne temporelle** est exprimée en unités de watt par mètre carré (W/m^2).

3.76
pression acoustique à la crête temporelle
p_{tp}
valeur maximale du module de la **pression acoustique instantanée** en un point particulier d'un champ acoustique.

Note 1 à l'article: La **pression acoustique à la crête temporelle** est exprimée en pascals (Pa).

3.77
intensité à la crête temporelle
I_{tp}
valeur maximale dans le temps de l'**intensité instantanée** en un point particulier dans un champ acoustique

Note 1 à l'article: L'**intensité à la crête temporelle** est exprimée en unités de watt par mètre carré (W/m^2).

3.78
intensité moyenne temporelle
$I_{\text{w},\Delta t/\text{s}}(t)$
valeur variant dans le temps de l'**intensité instantanée** moyennée sur un intervalle de temps d'une durée de Δt

$$I_{\text{w},\Delta t/\text{s}}(t) = \frac{1}{\Delta t} \int_{t-\Delta t/2}^{t+\Delta t/2} I(t')\,\text{d}t' \quad (8)$$

où

$I(t)$ est l'**intensité instantanée**;

Δt/s est la valeur numérique de déplacement de l'intervalle de temps en secondes;

t' est la variable d'intégration.

Note 1 à l'article: L'**intensité moyenne temporelle** variant dans le temps pendant un intervalle de temps de 20 s, par exemple, est notée par $I_{w,20}(t)$.

Note 2 à l'article: L'**intensité moyenne temporelle** est exprimée en unités de watt par mètre carré (W/m^2).

3.79
surface d'ouverture du transducteur
A_{TA}
surface active effective d'un **transducteur ultrasonique** dans le **plan d'ouverture du transducteur**

Note 1 à l'article: La **surface d'ouverture du transducteur** est exprimée en mètres carrés (m^2).

[SOURCE: IEC 61828:2020, 3.145]

3.80
plan d'ouverture du transducteur
plan orthogonal à l'**axe du faisceau** non dirigé et physiquement adjacent au **transducteur ultrasonique**

VOIR: Figure 1

Note 1 à l'article: Si le **transducteur ultrasonique** est plat, le plan est coplanaire avec la surface émettrice du **transducteur ultrasonique**. S'il est concave, le plan touche la périphérie de la surface émettrice. S'il est convexe, le plan est tangent au centre de la surface émettrice au point de contact.

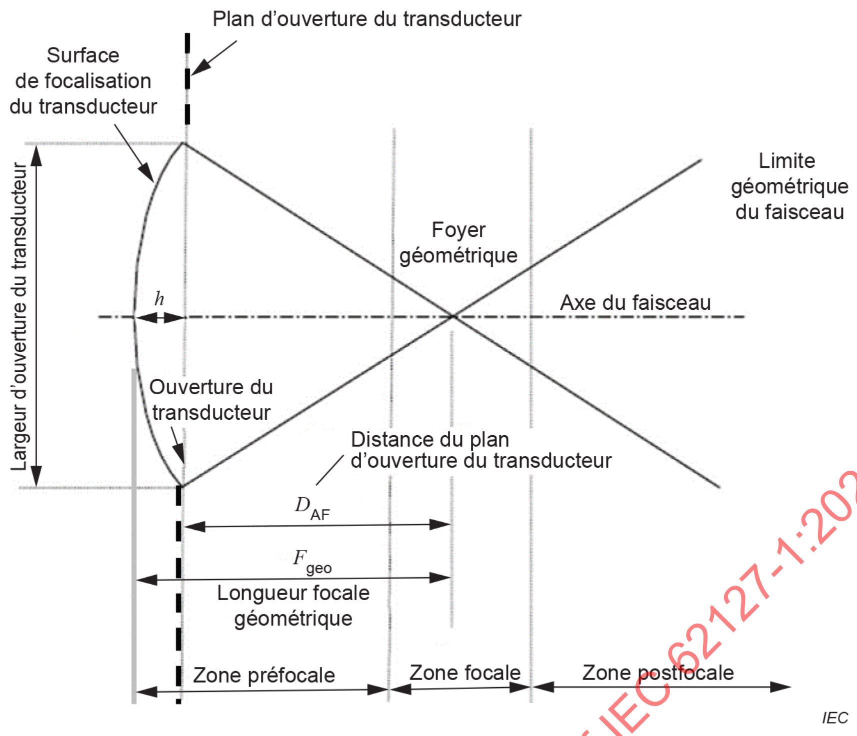
[SOURCE: IEC 61828:2020, 3.146]

3.81
largeur d'ouverture du transducteur
L_{TA}
largeur complète de l'ouverture du transducteur selon un axe spécifié orthogonal à l'**axe du faisceau** non dirigé au centre du transducteur

VOIR: Figure 3

Note 1 à l'article: La **largeur d'ouverture du transducteur** est exprimée en mètres (m).

[SOURCE: IEC 61828:2020, 3.148 modifiée – Les mots "au centre du transducteur" ont été ajoutés à la définition.]



Le rayon de courbure est $D = D_{AF} + h$.

[SOURCE: IEC 61828:2020]

Figure 3 – Paramètres pour la description d'un transducteur focalisant de géométrie connue

3.82
ensemble de transducteur
ensemble de pièces de l'**appareil de diagnostic médical à ultrasons** qui comporte le **transducteur ultrasonique** et/ou le **groupe d'éléments transducteurs ultrasoniques**, avec tous les composants intégrés (une lentille acoustique ou une colonne intégrée, par exemple)

Note 1 à l'article: L'**ensemble de transducteur** peut généralement être séparé du **pupitre de l'appareil à ultrasons**.

3.83
distance de transition
z_T
surface de l'ouverture divisée par π fois la longueur d'onde effective λ

[SOURCE: IEC 61828:2020, 3.153 modifiée – Les mots "fois la longueur d'onde effective" ont été ajoutés à la définition.]

3.83.1
distance de transition pour la conception
z_{TD}
<pour un **plan longitudinal** donné> **surface d'ouverture du transducteur,** A_{TA}, du **transducteur ultrasonique** divisée par π fois la longueur d'onde effective λ

$$z_{TD} = A_{TA}/(\pi\lambda) \quad (9)$$

Note 1 à l'article: Pour la conception, pour un **transducteur ultrasonique** sans apodisation à symétrie circulaire par rapport à l'**axe du faisceau**, la **surface d'ouverture de la source** est πa_e^2, où a_e est le rayon effectif. La **distance de transition** est donc $z_T = a_e^2/\lambda$.

Note 2 à l'article: Pour un transducteur à focalisation sphérique, la **distance de transition** est pratiquement la même, mais plus exactement, elle est $z_T = 2D^2\left(1-\sqrt{1-(a/D)^2}\right)/\lambda$ où D est le rayon de courbure.

Note 3 à l'article: Pour la conception, pour un **transducteur ultrasonique** rectangulaire sans apodisation présentant une **largeur d'ouverture du transducteur**, L_{TA1}, dans un **plan longitudinal** spécifié, la surface effective dans le plan est $(L_{TA1})^2$. Par conséquent, pour ce plan, la **distance de transition** est $z_{T1} = (L_{TA1})^2/(\pi\lambda)$. La **distance de transition** pour le **plan longitudinal** orthogonal incluant la deuxième **largeur d'ouverture du transducteur** est $z_{T2} = (L_{TA2})^2/(\pi\lambda)$.

Note 4 à l'article: Pour les transducteurs à apodisation et à symétrie régulière ou à fonction de pondération W (normalisée pour une valeur maximale de 1 pour la distribution de vitesse de particule), les **distances de transition** sont comme suit.

Pour un transducteur à symétrie circulaire ayant un rayon actif a:

$$z_T = \left(\frac{2}{\lambda}\right)\int_0^a W(r)r\,\mathrm{d}r$$

Pour un transducteur rectangulaire ayant une ouverture physique de longueur L dans un plan longitudinal donné, par exemple xz:

$$z_T = \left(\frac{4}{\pi\lambda}\right)\left|\int_0^{L/2} W(x)\mathrm{d}x\right|^2$$

Note 5 à l'article: Pour des formes symétriques autres que les cas les plus courants de symétrie circulaire et de géométrie rectangulaire, la même définition de **distance de transition** peut être employée. Par exemple, pour des ouvertures à symétrie n ($n > 2$) telles que des hexagones ou octogones, la **distance de transition** dans un plan de symétrie perpendiculaire à un côté est égale à la surface de l'ouverture divisée par ($\pi\lambda$). Pour des réseaux annulaires à plusieurs anneaux, la surface équivalente est la surface totale (de tous les anneaux) de l'ouverture active. Dans les cas où un phasage unique est employé, tels que pour un réseau annulaire à changements de phase alternés (0° ou 180°) et à focalisation dirigée ou dans les cas où l'ouverture est de forme et de phasage inhabituels, un calcul de diffraction tridimensionnel est employé pour déterminer la largeur de faisceau minimale correspondant à la **distance de transition** appropriée.

Note 6 à l'article: La **distance de transition pour la conception** est exprimée en mètres (m).

[SOURCE: IEC 61828:2020, 3.153.1, modifiée – La Note 6 à l'article initiale été omise ici.]

3.83.2
distance de transition pour les mesurages

z_{TM}

<pour un **plan longitudinal** donné> **surface d'ouverture de la source**, A_{SAeff}, du **transducteur ultrasonique** divisée par π fois la longueur d'onde effective λ

$$z_{TM} = A_{SAeff}/(\pi\lambda) \tag{10}$$

Note 1 à l'article: Pour les mesurages dans chaque **plan longitudinal** spécifié, la **largeur d'ouverture de la source** dans ce plan est utilisée où $z_{T1} = (L_{SA1})^2/(\pi\lambda)$. Dans l'autre plan orthogonal, $z_{T2} = (L_{SA2})^2/(\pi\lambda)$.

Note 2 à l'article: La **distance de transition pour les mesurages** est exprimée en mètres (m).

[SOURCE: IEC 61828:2020, 3.153.2]

3.84
projecteur ultrasonore
ensemble comprenant un **transducteur ultrasonique** et les parties associées pour une application locale d'**ultrasons** à un patient

[SOURCE: IEC 60601-2-5:2009, 201.3.214, modifiée – Une note dans la définition originale a été supprimée.]

3.85
pupitre d'appareil à ultrasons
ensemble électronique auquel l'**ensemble de transducteur** est associé

3.86
ligne d'exploration ultrasonique
<pour les systèmes explorateurs> **axe du faisceau** soit pour **un groupe d'éléments transducteurs ultrasoniques** particulier, soit pour une excitation particulière d'un **transducteur ultrasonique** ou d'un groupe d'**éléments transducteurs ultrasoniques**

Note 1 à l'article: Dans le présent document, une **ligne d'exploration ultrasonique** se réfère au parcours des impulsions acoustiques et non à une ligne sur une image sur l'écran de visualisation d'un système.

Note 2 à l'article: En général, le présent document part du principe qu'une ligne d'exploration se répète exactement après un certain nombre d'impulsions acoustiques. Si un **transducteur ultrasonique** ou un **groupe d'éléments transducteurs ultrasoniques** émet des ultrasons sans séquence de répétition, il n'est pas possible de caractériser un mode explorateur de la manière décrite dans le présent document. L'approche décrite à l'Annexe F peut être utile lorsque la synchronisation ne peut être obtenue.

Note 3 à l'article: Le cas dans lequel une seule excitation produit des faisceaux acoustiques qui se propagent le long de plusieurs **axes de faisceau** n'est pas pris en considération.

3.87
séparation des lignes d'exploration ultrasonique
s_{s}
<pour les systèmes explorateurs automatiques> distance entre les points d'intersection de deux **lignes d'exploration ultrasonique** consécutives du même type et une ligne spécifiée du **plan d'exploration**

Note 1 à l'article: Pour cette définition, il est pris pour hypothèse que les **lignes d'exploration ultrasonique** consécutives sont adjacentes du point de vue spatial. Cela n'est pas vrai pour tous les types d'appareil d'exploration.

Note 2 à l'article: La **séparation des lignes d'exploration ultrasonique** est exprimée en mètres (m).

3.88
transducteur ultrasonique
appareil qui permet de convertir l'énergie électrique en énergie mécanique dans la plage de fréquences ultrasonores et/ou, réciproquement, l'énergie mécanique en énergie électrique

3.89
élément de transducteur ultrasonique
élément d'un **transducteur ultrasonique** excité afin de produire un signal acoustique

3.90
groupe d'éléments transducteurs ultrasoniques
groupe d'éléments d'un **transducteur ultrasonique** excités simultanément afin de produire un signal acoustique

3.91
dimensions du groupe d'éléments transducteurs ultrasoniques
dimensions de la surface du groupe d'éléments d'un **transducteur ultrasonique**, incluant la distance entre les éléments et représentant donc les dimensions générales

Note 1 à l'article: Les **dimensions du groupe d'éléments transducteurs ultrasoniques** sont exprimées en mètres (m).

3.92
incertitude
paramètre associé au résultat d'un mesurage, qui caractérise la dispersion des valeurs qui peuvent être raisonnablement attribuées au mesurande

Note 1 à l'article: Voir ISO/IEC Guide 98-3:2008, 2.2.3.

4 Symboles

a_h	**taille efficace de l'hydrophone**
a_g	**rayon géométrique de l'hydrophone**
a_t	rayon efficace d'un **transducteur ultrasonique** sans focalisation
a_{max}	rayon efficace maximal pour une application particulière de **l'hydrophone**
arp	**période acoustique de répétition**
$A_{b,6}$,$A_{b,20}$	**surface du faisceau** correspondant à une surface pour -6 dB et pour -20 dB
A_g	surface géométrique d'un **transducteur ultrasonique**
A_{ob}	**surface du faisceau de sortie**
A_s	**surface d'exploration**
A_{SAeff}	**surface d'ouverture de la source**
A_{TA}	**surface d'ouverture du transducteur**
BW	**largeur de bande**
c	vitesse du son dans le milieu (en principe de l'eau)
C	capacité électrique en bout de câble d'un **hydrophone**
C_{el}	capacité d'entrée parallèle d'une charge électrique
d_{offset}	**distance de décalage**
f_{awf}	**fréquence acoustique, fréquence d'application acoustique**
f_p	**fréquence acoustique d'impulsion de crête**
f_t	**fréquence acoustique à moyenne temporelle**
F_a	**facteur de surface locale**
I	**intensité instantanée**
I_{ob}	**intensité du faisceau de sortie**
I_{pa}	**intensité moyenne de l'impulsion**
I_{sapa}	**intensité moyenne de l'impulsion de moyenne spatiale**
I_{sata}	**intensité dérivée de moyenne temporelle de moyenne spatiale**
I_{sppa}	**intensité dérivée de la moyenne d'impulsions de crête spatiale**
I_{ta}	**intensité dérivée de la moyenne temporelle**
I_{tp}	**intensité à la crête temporelle**
I_{spta}	**intensité dérivée de moyenne temporelle de crête spatiale**
I_{sptp}	**intensité à la crête spatiale et temporelle**
$I_{w,\Delta t/s}$	**intensité moyenne temporelle**

k	$2\pi/\lambda$
K_{sa}	facteur de correction de la moyenne spatiale
$L_{M_L}(f)$	**niveau de sensibilité en bout de câble**
$L_P(f)$	niveau de pression spectral
$\underline{LP}(f)$	fonction de filtrage passe-bas
L_{TA}	**largeur d'ouverture du transducteur**
L_{SA}	**largeur d'ouverture source**
$\underline{M}_c(f)$	**sensibilité en circuit ouvert en bout de câble**
$\underline{M}_L(f)$	**sensibilité en bout de câble**
n_{pps}	**nombre d'impulsions par ligne d'exploration ultrasonique**
n_{sl}	**nombre de lignes d'exploration ultrasonique** par image pour la répartition spatiale
p	**pression acoustique instantanée**
pii	**intégrale d'intensité d'impulsion**
$ppsi$	**intégrale de pression d'impulsion au carré**
p_m	**pression acoustique de crête moyenne**
p_{tp}	**pression acoustique à la crête temporelle**
prr	**régime de répétition des impulsions**
prp	**période de répétition des impulsions**
p_{spr}	**pression acoustique efficace à la crête spatiale**
p_{sptp}	**pression acoustique à la crête spatiale et temporelle**
p_{RMS}	**pression acoustique efficace**
$p_c(p+)$	**pression acoustique de compression de crête**
$pr(p_-)$	**pression acoustique de raréfaction de crête**
P	puissance acoustique totale
P_{beam}	puissance totale émise par une ligne d'exploration acoustique
R_{bh}	quotient de la largeur de faisceau d'impulsions –6 dB sur le diamètre efficace de l'**hydrophone**
s_s	**séparation des lignes d'exploration ultrasonique**
srp	**période de répétition des explorations**
srr	**régime de répétition des explorations**
t_d	**durée d'impulsion**
$\underline{U}_L(f)$	tension en bout de câble d'un **hydrophone**
v	vitesse acoustique instantanée
w_6, w_{12}, w_{20}	**largeur de faisceau** (niveaux à –6 dB, –12 dB et –20 dB)
X_{ob},Y_{ob}	**dimensions du faisceau de sortie**
z	distance entre un **hydrophone** et un **transducteur ultrasonique**
z_c	**distance** z_c
z_{ppsi}	**distance** z_{ppsi}

z_r	**distance z_r**
z_{spta}	**distance z_{spta}**
z_T	**distance de transition**
z_{TD}	**distance de transition pour la conception**
z_{TM}	**distance de transition pour les mesurages**
$\underline{Z}_h$	impédance de sortie électrique complexe d'un **hydrophone** ou d'un **ensemble d'hydrophones**
$\underline{Z}_L$	**impédance de charge électrique**
β	paramètre de non-linéarité
θ	angle d'incidence d'une onde ultrasonore par rapport à l'axe de l'**hydrophone**
λ	longueur d'onde acoustique dans un liquide
ρ	densité du milieu (en principe de l'eau)
σ_q	**paramètre de déformation locale**
ω	($2\pi f_{awf}$) fréquence circulaire

5 Exigences de mesure

5.1 Exigences relatives aux hydrophones et aux amplificateurs

5.1.1 Avertissement

Pour sélectionner un **hydrophone** et un amplificateur adaptés au type de mesure à réaliser, il faut assurer que les appareils sélectionnés répondent aux exigences ci-après. Les exigences relatives aux performances de l'**hydrophone** décrites dans le présent article complètent ou remplacent celles relatives aux **hydrophones** de l'IEC 62127-3.

5.1.2 Généralités

Le présent document estime qu'un **hydrophone** est un appareil qui répond aux ondes acoustiques aquatiques [voir IEV 801-32-26] de sorte que la tension de sortie soit proportionnelle à la pression acoustique. D'une manière générale, cette relation dépend de la fréquence et, par conséquent, si $\underline{M}_L(f)$ est la **sensibilité en bout de câble d'un hydrophone** (voir 3.25 et l'Annexe C), la **pression acoustique instantanée** $p(t)$ est liée à la tension en bout de câble mesurée $u_L(t)$ par

$$p(t) = \mathcal{F}^{-1}[\underline{U}_L(f) \,/\, \underline{M}_L(f)] \tag{11}$$

où

$\mathcal{F}^{-1}$ indique la transformée de Fourier inverse;

$\underline{U}_L(f)$ est le résultat de la transformée de Fourier de $u_L(t)$.

NOTE 1 Voir 5.1.7.2 et l'Annexe D pour mettre en œuvre cette méthode.

NOTE 2 Pour des raisons de complétude mathématique, il est nécessaire d'inclure dans la formule (11) l'opérateur de la partie réelle, Re, du côté droit. Cependant, pour le type de spectres concernés ici, les données du domaine temporel ne sont pas susceptibles de comprendre des composantes imaginaires, à l'exception d'un éventuel résidu numérique constant. Re est donc omis dans cette formule dans l'ensemble du document.

Si l'**hydrophone** ou l'**ensemble d'hydrophones** satisfait aux exigences d'une approximation de la bande étroite spécifiée en 5.1.7.1, la **pression acoustique instantanée** peut être déterminée par la formule (12):

$$p(t) = u_{\mathrm{L}}\ (t)\ /\ |\underline{M}_{\mathrm{L}}(f_{\mathrm{awf}})| \tag{12}$$

où

$|\underline{M}_{\mathrm{L}}(f_{\mathrm{awf}})|$ est le module de la **sensibilité en bout de câble** de l'**hydrophone** à la **fréquence d'application acoustique**.

5.1.3 Sensibilité d'un hydrophone

Si aucun **préamplificateur d'hydrophone** n'est utilisé, la sensibilité de l'**hydrophone** doit faire référence à la **sensibilité en bout de câble** et être déterminée pour des conditions de charge électrique particulières (voir 3.22).

Si un **préamplificateur d'hydrophone** est utilisé, la sensibilité de l'**hydrophone** doit faire référence à la **sensibilité en bout de câble** qui est liée à l'**ensemble d'hydrophones** particulier.

NOTE 1 La méthode présentée dans l'IEC 62127-3 peut être utilisée pour déterminer la **sensibilité en bout de câble**, en prenant pour hypothèse que la **sensibilité en circuit ouvert en bout de câble de l'hydrophone** est connue.

NOTE 2 Voir l'Article B.10 pour obtenir des exemples présentés sous forme de tableau des paramètres de spécification.

5.1.4 Réponse directionnelle d'un hydrophone

La réponse directionnelle de l'**hydrophone** doit être connue.

La symétrie de la réponse directionnelle doit être conforme à l'IEC 62127-3.

NOTE Il existe deux raisons de connaître la réponse directionnelle d'un **hydrophone**. En premier lieu, elle peut être nécessaire dans le cadre des modes opératoires de caractérisation du champ décrits à l'Annexe B, auquel cas, il est nécessaire de connaître la réponse directionnelle à la **fréquence d'application acoustique** appropriée. En second lieu, la réponse directionnelle permet de déduire la **taille efficace de l'hydrophone**.

5.1.5 Taille efficace de l'hydrophone

La **taille efficace de l'hydrophone** doit être connue et déterminée en suivant la méthode décrite dans l'IEC 62127-3.

5.1.6 Choix de la taille de l'élément actif d'un hydrophone

5.1.6.1 Généralités

Le choix de la **taille efficace de l'hydrophone** pour une application particulière doit être déterminée en considérant ce qui suit.

Dans l'idéal, il convient que la taille efficace de l'élément soit inférieure ou comparable à un quart de la longueur d'onde acoustique, de sorte que les variations de phase et d'amplitude ne participent pas de manière significative aux **incertitudes** de mesure.

Compte tenu du large éventail des types de **transducteur ultrasonique**, il n'est pas possible d'établir une relation simple entre la taille optimale de l'élément efficace de l'**hydrophone** et les paramètres tels que la dimension du **transducteur ultrasonique**, la longueur d'onde acoustique et la distance du **transducteur ultrasonique**. Toutefois, dans le **champ lointain**, il est raisonnable d'assouplir le critère ci-dessus. Dans le cas des **transducteurs ultrasoniques** circulaires, le critère ci-dessous peut être utilisé comme référence pour déterminer le rayon efficace maximal a_{max} de l'élément actif d'un **hydrophone**. a_{max} est donné par la formule (13):

$$a_{max} = \frac{\lambda}{8a_1}\left(l^2 + a_1^2\right)^{1/2} \tag{13}$$

où

a_1 est le rayon efficace du **transducteur ultrasonique**;

l est la distance entre l'**hydrophone** et la face du **transducteur ultrasonique**;

λ est la longueur d'onde acoustique correspondant à la **fréquence d'application acoustique**.

Voir [2][1] et [3].

Dans le cas d'un **transducteur ultrasonique** à focalisation, la relation ci-dessus peut toujours être utilisée.

Dans le cas d'un **transducteur ultrasonique** à élément non circulaire, la relation ci-dessus peut toujours être utilisée en remplaçant a_1 par la moitié de la **dimension** maximale **du transducteur ultrasonique** ou la **dimension** maximale **du groupe d'éléments transducteurs ultrasoniques**.

Les exigences liées à la taille de l'élément actif de l'**hydrophone** sont assouplies pour les mesurages des champs ultrasoniques générés par les systèmes de physiothérapie (voir 8.3.1).

Pour obtenir des données expérimentales représentatives, voir [1].

5.1.6.2 Effet de la moyenne spatiale

L'exigence pratique d'un rapport signal-bruit pertinent ou d'autres considérations peuvent amener à utiliser un **hydrophone** dont la taille d'un élément actif est supérieure à celle recommandée ci-dessus. Dans ce cas, il convient de faire attention lors de l'interprétation des mesurages, un **hydrophone** piézoélectrique étant un détecteur sensible à la phase qui intègre la pression acoustique complexe à son élément actif.

Si l'**hydrophone** est translaté de la position de réception maximale du signal selon une direction perpendiculaire à l'**axe du faisceau** et sur une distance égale à la **taille efficace de l'hydrophone**, il convient que le signal diminue de moins de 1 dB. Si ce n'est pas le cas, il convient de corriger la moyenne spatiale. Voir Annexe E.

Il est également possible d'améliorer les corrections en corrigeant la diffraction, voir [2], [3], [4], [5].

L'effet de la moyenne spatiale peut également être traité par déconvolution spatiale de l'ouverture de l'**hydrophone**, comme cela est proposé dans [6], [7], [8]. Toutefois, dans des cas pratiques, cette méthode peut poser des problèmes de rapport signal-bruit.

[1] Les chiffres entre crochets se réfèrent à la Bibliographie.

Pour les **formes d'onde des impulsions acoustiques** non linéaires à large bande, il convient d'appliquer la méthode de filtrage spectral inverse (voir l'Article E.2) pour corriger la moyenne spatiale.

5.1.7 Largeur de bande

5.1.7.1 Approximation de la bande étroite

Les approximations de la bande étroite doivent être considérées comme appropriées lorsque le **paramètre de déformation locale** est inférieur à 0,5 (voir 7.2.4).

Dans ce cas, il est suffisant de considérer la valeur de sensibilité à la **fréquence d'application acoustique** comme représentative de la valeur de sensibilité à toutes les fréquences à l'étude.

NOTE 1 Lors du mesurage des signaux acoustiques à bande étroite, il est retenu par hypothèse que toutes les composantes significatives de la fréquence à l'intérieur du signal se trouvent à des fréquences proches de la **fréquence d'application acoustique**. Dans ce cas, la **sensibilité en bout de câble de l'hydrophone** varie peu.

NOTE 2 L'hypothèse de simplification donnée ci-dessus peut également être utilisée lors du mesurage des champs acoustiques à contenu fréquentiel plus large, à condition que la **sensibilité en bout de câble** de l'**hydrophone** ne présente que des variations limitées sur la plage de fréquences nécessaires à la représentation précise du signal acoustique.

Si la valeur du **paramètre de déformation locale** est supérieure à 0,5 (voir 7.2.4), **le niveau de sensibilité en bout de câble** de l'**hydrophone** ou de l'**ensemble d'hydrophones** doit varier de moins de ±3 dB sur la plage de fréquences (f) allant d'une octave au-dessous à trois octaves au-dessus de la **fréquence d'application acoustique**, dans laquelle le point de référence 0 dB se trouve à la **fréquence d'application acoustique, f_{awf}**. En d'autres termes, pour

$$f_{\text{awf}}/2 \leq f \leq 8\, f_{\text{awf}} \tag{14}$$

$$L_{M_{\text{L}}}\left(f_{\text{awf}}\right) - 3\ \text{dB} \leq L_{M_{\text{L}}}\left(f\right) \leq L_{M_{\text{L}}}\left(f_{\text{awf}}\right) + 3\ \text{dB} \tag{15}$$

où $L_{M_{\text{L}}}\left(f\right) = 20\log_{10}\dfrac{\left|\underline{M}_{\text{L}}\left(f\right)\right|}{M_{\text{ref}}}\ \text{dB}$ et $M_{\text{ref}} = 1\dfrac{\text{V}}{\text{Pa}}$.

NOTE 3 Une explication scientifique justifie l'utilisation d'une plage étendue $f_{\text{awf}}/16 \leq f \leq 8 f_{\text{awf}}$ (c'est-à-dire, de quatre octaves au-dessous à trois octaves au-dessus de f_{awf}) sur la base de [9] et [10] (voir également l'Annexe A). Toutefois, les données d'étalonnage de l'**hydrophone** déterminées expérimentalement ne sont disponibles que pour une **largeur de bande** limitée, par exemple de 1 MHz à 100 MHz. Pour apprécier si l'approximation à bande étroite au moyen des formules (14) et (15) est appropriée, l'extrapolation de la réponse en fréquence de l'**hydrophone** peut être appliquée comme méthode alternative conformément aux spécifications de 5.1.7.2.2 y compris les Notes 1, 2 et 3, ainsi que de l'Annexe D pour les mesurages à large bande, si cela est nécessaire. En d'autres termes, l'extrapolation de $\underline{M}_{\text{L}}(f)$ peut être utilisée pour couvrir les fréquences f hors de la plage d'étalonnage disponible, au maximum en dessous de la moitié de la **fréquence d'application acoustique** vers zéro et au-dessus de la plus petite des fréquences suivantes: quatre fois la **fréquence d'application acoustique** et 100 MHz vers la fréquence Nyquist f_{Nyquist}, par exemple pour $0 \leq f < f_{\text{awf}}/2$ et pour min [4 f_{awf}, 100 MHz] $< f \leq f_{\text{Nyquist}}$. Des informations détaillées sur les considérations relatives à une extrapolation appropriée sont disponibles en D.4.2.

Si les exigences liées à l'approximation à bande étroite ne sont pas satisfaites, la méthode de mesure à large bande spécifiée en 5.1.7.2 doit être appliquée.

Si la méthode de mesure à large bande de 5.1.7.2 est mise en œuvre dans le système de mesure, elle peut être utilisée pour toutes les situations y compris celles couvertes par les exigences d'approximation à bande étroite.

Les mesurages effectués conformément aux exigences de la première édition de l'IEC 62127-1 peuvent avoir pris en considération les contributions en fréquence à hauteur de 40 MHz seulement. Les exigences modifiées de la présente seconde édition n'impliquent pas que ces mesurages antérieurs doivent être répétés dans le cadre des mesurages de la sortie des appareils qui ont déjà été caractérisés conformément à la première édition. Au besoin, l'erreur systématique de la largeur de bande limitée peut dans ces cas être attribuée à une contribution d'**incertitude** supplémentaire.

NOTE 4 Voir 8.2.4 pour des considérations spécifiques à l'appareil de diagnostic à faible émission acoustique.

5.1.7.2 Mesurages à large bande

5.1.7.2.1 Généralités

Si les exigences liées à l'approximation à bande étroite ne peuvent être satisfaites, l'**incertitude** des mesurages peut devenir beaucoup trop importante à cause de la largeur de bande limitée de l'**hydrophone** et de la variation de la sensibilité de l'**hydrophone** dépendant de la fréquence. La conversion de la tension en pression doit alors être effectuée à l'aide de la sensibilité de l'**hydrophone** dépendant de la fréquence et du contenu fréquentiel de la **forme d'onde des impulsions acoustiques**. La méthode de mesure fondée sur la déconvolution de la forme d'onde acquise avec la réponse de l'**hydrophone**, telle que décrite ici en 5.1.7.2 et à l'Annexe D, produit des résultats plus exacts. Pour effectuer la déconvolution, les aspects spécifiques du traitement des données d'étalonnage de l'hydrophone, du filtrage de régularisation des spectres du signal et de la détermination de l'**incertitude** doivent être pris en considération selon le 5.1.7.2.2, le 5.1.7.2.3 et le 5.1.7.2.4.

5.1.7.2.2 Largeur de bande de déconvolution

L'application de la formule (11) pour déterminer la **forme d'onde des impulsions acoustiques** exige la division complexe du spectre de tension $\underline{U}_{\mathrm{L}}(f)$ par la sensibilité $\underline{M}_{\mathrm{L}}(f)$. Pour cette opération, les ensembles de données doivent correspondre, c'est-à-dire que l'incrément de fréquence et la plage de fréquences des deux spectres doivent être identiques. L'incrément de fréquence de $\underline{U}_{\mathrm{L}}(f)$ dépend de la longueur de la **forme d'onde des impulsions acoustiques** acquise (y compris l'ajout de zéros, le cas échéant) et la plage de fréquences s'étend de 0 à la fréquence Nyquist associée à la fréquence d'échantillonnage utilisée. Les données d'étalonnage d'**hydrophone**, $\underline{M}_{\mathrm{L}}(f)$, obtenues expérimentalement peuvent toutefois fournir des incréments et des plages de fréquences différents. Si nécessaire, les données d'étalonnage peuvent être interpolées entre les points de données de sensibilité consécutifs disponibles pour l'**hydrophone** (voir Annexe D). S'il y a lieu, l'extrapolation de $\underline{M}_{\mathrm{L}}(f)$ peut être utilisée pour couvrir les fréquences f hors de la plage d'étalonnage disponible, au maximum en dessous de la moitié de la **fréquence d'application acoustique** vers zéro et au-dessus de la plus petite des fréquences suivantes: quatre fois la **fréquence d'application acoustique** et 100 MHz vers la fréquence Nyquist f_{Nyquist}, par exemple pour $0 \leq f < f_{\mathrm{awf}}/2$ et pour min [4 f_{awf}, 100 MHz] $< f \leq f_{\mathrm{Nyquist}}$. Des informations détaillées sur les considérations relatives à une extrapolation appropriée sont disponibles en D.4.2.

NOTE 1 La limite inférieure maximale de 100 MHz pour l'extrapolation à des fréquences supérieures à celles exigées ci-dessus repose sur l'hypothèse d'une disponibilité de certificats d'étalonnage de l'hydrophone jusqu'à 100 MHz au moment de la publication du présent document. Si seule une limite supérieure minimale est disponible à cette période de publication, une telle limite peut être utilisée pour des raisons pratiques.

NOTE 2 Des techniques d'étalonnage par impulsions secondaires ont été développées [11],[12] et peuvent être appliquées par l'utilisateur d'hydrophone pour déterminer la sensibilité de chaque hydrophone dans les plages de fréquences dans lesquelles le service d'étalonnage n'est pas disponible. Les mêmes techniques peuvent être utilisées, en général, pour extrapoler les données d'étalonnage de l'hydrophone, et pour vérifier la conformité à l'approximation à bande étroite par les formules (14) et (15).

NOTE 3 Pour certains types d'hydrophones, la variation de la sensibilité à une fréquence plus élevée peut éventuellement être estimée à partir des données d'étalonnage obtenues à des fréquences plus basses. Par exemple, au-dessus de la fréquence de résonance d'un hydrophone à membrane, la sensibilité est susceptible de suivre une tendance prévisible. Dans de tels cas, la prévision de la sensibilité peut être utilisée à la place des mesurages directs tant que l'**incertitude** de la prévision est prise en compte, sur la base de mesurages d'étalonnage d'hydrophones similaires dans toute la plage de fréquences dans lesquelles la prévision est utilisée.

5.1.7.2.3 Régularisation

D’un point de vue mathématique, la déconvolution est un problème inverse mal posé, qui dans le domaine temporel discret entraîne un problème d’estimation mal traité [13], [14]. Par exemple, à très haute fréquence, le signal acquis de l’**hydrophone** peut encore comporter une certaine contribution de bruit, mais la sensibilité peut être proche de zéro. La formule (11) conduit alors à un impact important de ce bruit dans la déconvolution; voir l’Annexe D pour un exemple de forme d’onde. Pour obtenir des formes d’onde avec un bruit global acceptable, il est généralement nécessaire de procéder à un filtrage passe-bas approprié, ce qui réduit également l’apparition d’oscillations de Gibbs. En incluant une telle régularisation, la formule (11) est alors étendue vers

$$p(t) = \mathcal{F}^{-1}\left(\underline{LP}(f) \cdot \frac{\underline{U}_{\mathrm{L}}(f)}{\underline{M}_{\mathrm{L}}(f)} \right) \tag{16}$$

où $\underline{LP}(f)$ désigne la fonction de filtrage passe-bas à valeurs complexes. Différentes fonctions de filtrage peuvent être utilisées pour la déconvolution des signaux de l’**hydrophone** [14], [15], [16], [17], [18], [19], [20], [21]. Étant donné que tout filtrage passe-bas induit une limitation supplémentaire de la **largeur de bande** et donc éventuellement une réduction des parties de la pression de crête de la forme d’onde, la fréquence de coupure du filtre doit être aussi grande que possible tout en assurant une suppression du bruit suffisante pour obtenir des **incertitudes** raisonnables pour les paramètres de la forme d’onde. La fréquence de coupure à -3 dB du filtrage passe-bas doit être supérieure ou égale à 8 fois la **fréquence d’application acoustique** f_{awf} déterminée à partir du spectre de pression sans filtrage passe-bas.

NOTE 1 Dans les situations de mesure où la répétition des impulsions est stable, la suppression du bruit à haute fréquence peut être améliorée en augmentant la moyenne des signaux.

NOTE 2 En général, la réduction de la **largeur de bande** des formes d’ondes ultrasonores déformées de façon non linéaire par un filtrage passe-bas supplémentaire a plus d’impact sur la pression de compression de crête que sur la pression de raréfaction de crête et les données d’intensité dérivées.

NOTE 3 Pour les formes d’onde à déformation non linéaire de grande amplitude des ultrasons thérapeutiques de haute intensité ou de la lithotritie comprenant jusqu’à 100 harmoniques, des fréquences de coupure plus élevées que 8 fois la **fréquence d’application acoustique** sont nécessaires pour éviter la coupure des parties de la forme d’onde de compression de crête, ainsi que la contribution excessive systématique de l’**incertitude** de la régularisation. Les spécifications sont fournies en 8.3.2.

NOTE 4 Un type de filtre numérique convenable pour de nombreuses applications revêt la forme $\underline{LP}(f) = 1 \Big/ \left(1 + \frac{i f}{f_{\mathrm{g}}}\right)^2$, avec $i = \sqrt{-1}$ et f_{g} désignant la fréquence de coude à -6 dB. La fréquence de coude à -3 dB est alors approximativement f_{g} /1,555 [17].

NOTE 5 En principe, le choix du filtre de régularisation et de la fréquence de coupure peut être effectué en optimisant l’**incertitude** globale de la forme d’onde déconvolutionnée, y compris les composantes de bruit et de régularisation partiellement concurrentes [14].

NOTE 6 Parmi les paramètres acoustiques énumérés en 7.2.1, la **pression acoustique de compression de crête** est la plus susceptible d’être affectée par le choix du filtre de régularisation.

5.1.7.2.4 Estimation de l’incertitude de la méthode de mesure à large bande

En raison de l’application des transformées de Fourier et des transformées de Fourier inverses, du filtrage de régularisation, ainsi que des données d’étalonnage à valeurs complexes de l’**hydrophone**, l’estimation de l’**incertitude** de la méthode de mesure à large bande peut sembler moins nette que dans d’autres situations. Cependant, une évaluation de l’**incertitude** conformément au Guide pour l’expression de l’incertitude de mesure (ISO/IEC Guide 98-3 et ISO/IEC Guide 98-3/Supplément 2 [22]) peut être réalisée en utilisant des formules fermées pour la propagation des **incertitudes** lorsque des transformées de Fourier discrètes et inverses sont appliquées et un outil logiciel libre GUM2DFT[2] est disponible [21]. Cette méthode permet, par exemple, de propager dans le domaine temporel les **incertitudes** dépendant de la fréquence et associées aux données d'étalonnage de l'**hydrophone** fournies pour le module et la phase dans le domaine fréquentiel.

L'utilisation d'un filtrage numérique passe-bas supplémentaire pour régulariser le problème de déconvolution introduit une contribution d'**incertitude** supplémentaire dans le mode opératoire de mesure et d'évaluation des données. L'impact de l'erreur systématique induite peut être évalué quantitativement, par exemple, en prenant en considération dans le domaine fréquentiel une fonction de limite supérieure continue pour le spectre d'amplitude de la pression, sur la base d'une approche simple de fonctions de base uniparamétriques. De même, il peut l'être en intégrant d'autres connaissances préalables, telles que les composantes spectrales décroissant de façon monotone avec la fréquence prévue pour les **formes d'onde des impulsions acoustiques** à déformation non linéaire, et la signature type du bruit à haute fréquence par rapport à la contribution du signal de forme d'onde [14].

5.1.8 Linéarité

Il convient d'étendre la réponse linéaire, telle que définie dans l'IEC 62127-3, à 5 MPa.

La limite supérieure de la plage dynamique connue doit être indiquée, en particulier si elle est inférieure à 5 MPa.

5.1.9 Amplificateur de signal de l'hydrophone

5.1.9.1 Généralités

Les amplificateurs **d'hydrophone** doivent satisfaire aux exigences de performances suivantes.

5.1.9.2 Exigences pour tous les amplificateurs

Le gain de l'amplificateur doit permettre à l'**ensemble d'hydrophones** de satisfaire aux exigences données en 5.1.7.

Le niveau de sensibilité ne doit pas varier de plus de 0,5 dB par incrément de fréquence de 100 kHz dans la **largeur de bande** indiquée. L'exigence peut être vérifiée en utilisant une représentation appropriée de la réponse en fréquence qui permet de résoudre tous les détails importants de la dépendance de la fréquence.

Avec un signal d'entrée dans la plage dynamique de 50 dB, la linéarité doit être de ±0,3 dB.

Le bruit spectral mesuré généré par l'**ensemble d'hydrophones** doit être suffisamment faible pour permettre de procéder aux mesurages avec un rapport signal-bruit adéquat, quelle que soit la fréquence dans la **largeur de bande** prise en considération.

Les paramètres de performance suivants doivent être précisés:

– le gain en fonction de la fréquence;
– l'impédance d'entrée en fonction de la fréquence, les composantes réelles et imaginaires (Z_L) (voir 3.22) ou les composantes capacitives et résistives parallèles équivalentes;
– l'impédance de sortie.

[2] Cette information est donnée à l'intention des utilisateurs du présent document et ne signifie nullement que l'IEC approuve ou recommande l'emploi exclusif du produit cité.

5.1.9.3 Exigences supplémentaires pour les amplificateurs différentiels

Les exigences relatives à l'impédance données ci-dessus doivent s'appliquer, sauf que l'impédance est mesurée entre les deux entrées actives.

La réjection en mode commun doit être de 40 dB au moins (par rapport à l'entrée) dans la plage de fréquences d'une octave au-dessous à deux octaves au-dessus de f_{awf}. Voir [23], [24].

5.1.10 Longueur du câble de l'hydrophone et amplificateurs

Un câble de raccordement de longueur et d'impédance caractéristique garantissant que la résonance électrique dans le câble de raccordement n'a aucun impact sur la **largeur de bande** définie de l'**hydrophone** ou de l'**ensemble d'hydrophones** doit être choisi. Le câble doit également être terminé de manière appropriée.

Pour réduire le plus possible l'effet de résonance dans le câble de raccordement, la longueur du câble de l'**hydrophone** (en mètres) doit être nettement inférieure à $50/(f_{awf}+BW_{20})$, où f_{awf} est la **fréquence d'application acoustique** (en MHz) et BW_{20} la **largeur de bande** à –20 dB (en MHz) du signal de l'**hydrophone**. Dans la plupart des cas, un câble ≤ 15 cm de longueur est généralement utilisé (voir [25]).

NOTE 1 Une attention particulière est accordée à la qualité de l'impédance de sortie de l'**hydrophone**/amplificateur par rapport à l'impédance d'entrée de l'appareil de mesure connecté.

NOTE 2 Les méthodes données à l'Annexe D peuvent être utilisées pour corriger les effets de la **largeur de bande** finie de l'**hydrophone**/amplificateur sur les ondes qui font l'objet de déformation à partir de la propagation non linéaire.

5.2 Exigences de positionnement et bains-marie

5.2.1 Généralités

Différents systèmes peuvent être utilisés pour monter le **transducteur ultrasonique** et l'**hydrophone**. Les exigences générales de performance liées à ces systèmes sont spécifiées ici et sont considérées comme optimales pour les besoins du présent document. D'autres systèmes de positionnement peuvent être utilisés, à condition de démontrer leur équivalence à ceux présentés dans ce paragraphe.

L'Annexe J présente la configuration simple d'un réservoir, d'un **transducteur ultrasonique** et d'un **hydrophone** destinée à indiquer uniquement les axes de coordonnées et degrés de liberté auxquels fait référence le présent document.

5.2.2 Systèmes de positionnement

5.2.2.1 Positionnement du transducteur

Le **transducteur ultrasonique** en essai doit être placé sur un système de positionnement, de telle sorte que sa face soit totalement immergée dans le bain-marie et qu'il se trouve à une distance telle d'une surface adjacente (une interface eau/air, par exemple) que les ultrasons réfléchis sur cette surface ne gênent pas le principal signal reçu. Si la surface est parallèle à l'**axe du faisceau**, les critères ci-dessous doivent être satisfaits.

Si z est la distance entre l'élément actif d'un **hydrophone** et la face d'un **transducteur ultrasonique** et que t est la durée entre l'arrivée de l'impulsion directe au niveau de l'**hydrophone** et la fin de la période d'acquisition du mesurage, la distance minimale, h, entre l'**axe du faisceau** et la surface réfléchissante doit être déterminée par (voir la formule (17))

$$(z^2 + 4h^2)^{1/2} - z > ct \tag{17}$$

Il est préférable d'immerger le transducteur et de ne pas placer de membrane entre la face du **transducteur ultrasonique** et le bain-marie. Toutefois, si une membrane est nécessaire, il convient qu'elle soit aussi fine et aussi proche que possible de la surface frontale du **transducteur ultrasonique**. Il convient de garantir un couplage acoustique rapproché à l'aide d'un agent de couplage à base d'eau, en prenant soin d'éliminer les bulles d'air. Il convient de corriger les mesurages des paramètres acoustiques pour tenir compte de l'atténuation de transmission de la membrane.

5.2.2.2 Positionnement de l'hydrophone

L'**hydrophone** doit être configuré dans le système de positionnement par coordonnées, de sorte que la direction de la sensibilité maximale de l'**hydrophone** soit approximativement parallèle à la direction prévue de l'**axe du faisceau** du **transducteur ultrasonique** à mesurer.

NOTE Pour éviter les effets sur les mesurages réalisés sur des champs à ondes entretenues dus à la réflexion des ultrasons sur la surface des **hydrophones** à membrane, l'**hydrophone** peut être incliné. L'inclinaison assure que les ultrasons réfléchis ne gênent pas le transducteur de manière significative ou ne se réfléchissent pas sur la face du transducteur, produisant des effets d'interférence. Deux méthodes qui permettent de déterminer la rotation exigée sont présentées à l'Annexe B.

5.2.2.3 Positionnement spatial

L'**hydrophone** et/ou le **transducteur ultrasonique** doivent être placés sur un système de positionnement qui permet de les positionner l'un par rapport à l'autre en un point souhaité d'un espace avec les degrés de liberté suivants:

a) positionnement spatial le long de trois axes orthogonaux (nommés x, y et z), l'un d'eux (appelé axe z) étant l'**axe du faisceau** de l'élément actif du **transducteur ultrasonique**;
b) pour permettre de reproduire les positions, il convient d'équiper tous les systèmes de translation et de rotation d'indicateurs de position;
c) il convient que la répétabilité du positionnement soit 0,10λ ou 0,05 mm, selon la plus faible de ces deux valeurs.

NOTE 1 Après l'alignement, il est attendu que l'axe z soit parallèle à l'**axe du faisceau** du **transducteur ultrasonique**.

NOTE 2 Il est possible d'assouplir les exigences de reproductibilité pour de nombreux mesurages. Une base raisonnable consiste à associer la précision du système de positionnement au diamètre de l'élément actif de l'**hydrophone**. Dans la direction perpendiculaire à la direction de propagation des ultrasons, une précision équivalente à 10 % du diamètre de l'élément actif de l'**hydrophone** est en général pertinente. De même, dans une direction parallèle à la direction de propagation, une précision équivalente au diamètre de l'élément actif est en général pertinente.

5.2.3 Bain-marie

5.2.3.1 Généralités

La taille du récipient de mesure doit être telle que le **transducteur ultrasonique** et l'**hydrophone** puissent se déplacer l'un par rapport à l'autre de manière suffisamment ample pour permettre de placer l'élément actif de l'**hydrophone** en tout point du champ acoustique auquel les mesurages sont exigés.

Des moyens doivent être prévus pour réduire le plus possible les effets sur le mesurage de la réflexion qui provient des parties du bain-marie ou des parois (voir également 5.2.3.2).

Dans une direction parallèle à l'**axe du faisceau** pour les systèmes explorateurs non automatiques ou à l'axe de symétrie du **plan azimutal** pour les systèmes explorateurs automatiques, il convient que la paroi du bain-marie se trouve à une distance du **transducteur ultrasonique** sensiblement supérieure (de 30 % à 100 %) à la distance de séparation maximale entre le **transducteur ultrasonique** et l'**hydrophone**.

Dans une direction perpendiculaire à l'**axe du faisceau** pour les systèmes explorateurs non automatiques ou à l'axe de symétrie du **plan azimutal** pour les systèmes explorateurs automatiques, il convient que la paroi du bain-marie se trouve à une distance sensiblement supérieure (de 30 % à 100 %) à la distance maximale entre l'**hydrophone** et l'**axe du faisceau** dans le cas des systèmes explorateurs non automatiques ou d'une **ligne d'exploration** extrême dans le cas des systèmes explorateurs automatiques.

NOTE 1 Il est également nécessaire de prendre en considération la taille de l'**hydrophone**. Pour les **hydrophones** à membrane, une surlargeur dans la direction perpendiculaire à l'**axe du faisceau** peut s'avérer nécessaire.

NOTE 2 Les critères de choix de la taille du bain-marie mentionnés ci-dessus sont adaptés pour les **durées d'impulsion** inférieures à 10 µs. Pour les **durées d'impulsion** plus longues, voir 5.2.2.1 et [26].

5.2.3.2 Matériau de revêtement

Il convient de réaliser les mesurages dans des conditions approchant celles d'un champ acoustique libre. Dans le cas des **transducteurs ultrasoniques** excités dans des conditions à ondes entretenues, il convient de placer les absorbeurs acoustiques de sorte qu'ils absorbent autant d'incidence ultrasonore des parois du bain-marie que possible. Pour les **transducteurs ultrasoniques** pulsés, et lorsque les techniques qui utilisent les signaux à déclenchement périodique sont employées pour détecter le signal de l'**hydrophone**, il n'est pas fondamental d'utiliser des absorbeurs acoustiques. Toutefois, il est souvent conseillé de placer des absorbeurs sur les parois du bain-marie, à des endroits qui permettent d'absorber le champ acoustique incident principal qui provient du **transducteur ultrasonique**.

Les essais suivants peuvent être utilisés pour déterminer la nécessité de recourir à des absorbeurs acoustiques, selon le critère ci-après:

Il convient d'utiliser des absorbeurs acoustiques si les ultrasons réfléchis augmentent le niveau général de bruit de fond du signal de l'**hydrophone** de manière uniforme, ou si des signaux parasites de l'**hydrophone** sont détectés aux alentours du principal signal reçu.

Un essai pratique qui permet de détecter la présence de signaux parasites consiste à modifier la distance entre le **transducteur ultrasonique** et l'**hydrophone** tout en observant le signal avec un oscilloscope. Il a été observé que certains signaux parasites se déplacent à au moins deux fois la vitesse du signal reçu directement, et que d'autres sont reçus dans un intervalle de temps incorrect lors de la comparaison de la distance entre le **transducteur ultrasonique** et l'**hydrophone**. Cet essai ne peut être réalisé que sur des systèmes à impulsions.

Avec l'excitation à ondes entretenues, il est nécessaire d'observer les déphasages et la déformation du signal principal lorsque le **transducteur ultrasonique** est déplacé. Une structure à ondes stationnaires partielles peut également être observée dans de nombreux cas.

Les conditions en champ libre sont suffisamment satisfaites lorsque l'écho global est réduit de plus de 25 dB. Différentes méthodes peuvent être utilisées pour vérifier la conformité de la réduction de l'écho des matériaux de revêtement utilisés, au présent paragraphe. Les procédures décrites dans l'IEC TS 63081 peuvent être appliquées pour vérifier l'amortissement ou la diffusion des matériaux.

5.2.3.3 Qualité de l'eau

Pour les mesurages réalisés dans des champs de haute pression ou sur des **transducteurs ultrasoniques** excités par ondes entretenues à puissance élevée, les effets de cavitation peuvent être significatifs et, dans ce cas, il convient d'utiliser de l'eau dégazée (voir Annexe G pour des recommandations).

Il convient de distiller ou de déioniser l'eau à une température connue. Si un **hydrophone** PVDF (polyfluorure de vinylidène) à membrane non blindé du point de vue électrique à une seule couche est utilisé, il convient que la conductivité électrique de l'eau soit inférieure à 5 µS cm^{-1}.

5.3 Exigences liées aux systèmes d'acquisition et d'analyse des données

Les caractéristiques de transfert du système d'acquisition et d'analyse des données doivent permettre d'assurer que, en cas d'utilisation en combinaison avec l'**hydrophone**, le préamplificateur ou l'amplificateur, les exigences de 5.1.6 à 5.1.9 sont satisfaites pour la combinaison.

5.4 Recommandations concernant les appareils à ultrasons en cours de caractérisation

Si le balayage des systèmes explorateurs automatiques peut être "gelé", il convient de procéder à des mesurages acoustiques appropriés pour garantir l'absence de variation significative entre un faisceau "gelé" et un faisceau électronique.

NOTE 1 Cet exercice n'est pas futile et dépend du type de système explorateur. De même, il n'est pas possible de véritablement déterminer les paramètres de moyenne temporelle d'un faisceau "gelé".

Si un signal électronique synchronisé à l'excitation du **transducteur ultrasonique** ou du **groupe d'éléments transducteurs ultrasoniques** n'est pas disponible, d'autres méthodes peuvent être employées afin d'obtenir ce signal de déclenchement.

NOTE 2 Il s'agit de méthodes qui utilisent une bobine de détection électromagnétique externe ou un capteur acoustique auxiliaire placé dans le champ ultrasonique. Voir [27], [28], [29].

Si un **transducteur ultrasonique** ou un **groupe d'éléments transducteurs ultrasoniques** émet des ultrasons sans séquence de répétition, il n'est pas possible de synchroniser le système de mesure de la manière décrite dans le présent document. Un sous-ensemble de mesurages acoustiques, principalement représentés du point de vue de la sécurité, est décrit à l'Annexe F et peut être utile si la synchronisation est impossible.

Il convient de désactiver tous les systèmes qui contrôlent les émissions acoustiques du **transducteur ultrasonique** par suite d'une modification de l'impédance acoustique. Si cela n'est pas possible, il convient de tenir compte d'une **incertitude** de mesure supplémentaire.

6 Mode opératoire de mesure

6.1 Généralités

Les modes opératoires présentés dans le présent Article 6 et dans l'Article 7 sont particulièrement adaptés à la caractérisation des champs ultrasoniques qui utilisent des **hydrophones** piézoélectriques. D'autres modes opératoires qui reposent sur l'utilisation d'**hydrophones** piézoélectriques peuvent être utilisés, à condition de démontrer l'équivalence aux techniques présentées dans le présent Article 6.

6.2 Préparation et alignement

6.2.1 Préparation

Il peut être nécessaire de sceller différentes parties du **transducteur ultrasonique** pour éviter les voies d'eau, particulièrement autour du point d'entrée du câble si l'ensemble du dispositif est immergé. Il convient de suivre les conseils du fabricant.

Avant l'utilisation, il convient de vérifier l'absence de pollution sur les surfaces du **transducteur ultrasonique** et de l'**hydrophone**. En cas de pollution, il convient de nettoyer les surfaces conformément aux instructions du fabricant. Il convient de suivre toutes les précautions particulières liées à l'utilisation fiable des **hydrophones** ou des **transducteurs** qui peuvent être spécifiées par le fabricant ou que l'utilisateur peut avoir estimé nécessaires (l'immersion d'un **hydrophone** pendant un certain temps avant utilisation, par exemple).

Concernant l'insertion du **transducteur ultrasonique** et de l'**hydrophone** dans l'eau, il convient de veiller à assurer que toutes les bulles d'air ont disparu des faces actives. Au cours des mesurages, il convient de vérifier qu'aucune bulle n'apparaît.

6.2.2 Alignement d'un transducteur ultrasonique et d'un hydrophone

L'axe z de l'**hydrophone**, qui est dans la direction de la sensibilité maximale, doit être aligné parallèle à la direction de propagation des ultrasons. Un mode opératoire d'alignement correct est donné dans l'IEC 61828.

6.3 Mesurage

Procéder aux mesurages avec un **ensemble d'hydrophones** approprié. Observer en tout point pendant une durée suffisante pour qu'une partie représentative du signal acoustique soit échantillonnée. D'une manière générale, cela dure moins d'une seconde.

Vérifier que la **largeur de bande**, la fréquence d'échantillonnage et/ou la résolution temporelle du système d'acquisition sont suffisantes pour représenter avec exactitude le signal de l'**hydrophone**.

NOTE 1 Des oscilloscopes et des cartes de capture numériques de dernière génération sont désormais disponibles et permettent de capturer et d'analyser des enregistrements extrêmement longs. D'une manière générale, ce type d'appareil semble être le moyen le plus souple pour déterminer tous les paramètres nécessaires.

NOTE 2 Étant donné que le signal acoustique n'est plus réputé se répéter, l'échantillonnage temps équivalent n'est pas possible et, par conséquent, la **largeur de bande** numérique à impulsion unique a besoin d'être suffisante pour représenter avec exactitude le signal de l'**hydrophone**.

6.4 Analyse

6.4.1 Corrections de la largeur de bande limitée et de la résolution spatiale

Des corrections doivent être apportées si les mesurages sont affectés par une **largeur de bande** limitée (voir 5.1.7) ou des résonances du câble (voir 5.1.10). Lorsque les exigences liées à la bande étroite (voir 5.1.7.1) ne sont pas satisfaites, la méthode de déconvolution doit être appliquée (voir 5.1.7.2).

Des corrections doivent être apportées si les mesurages sont affectés par les effets de la moyenne spatiale identifiés en 5.1.6.2. Les corrections doivent être apportées en suivant les méthodes données à l'Annexe E.

6.4.2 Incertitudes

Pour évaluer et exprimer l'**incertitude** de l'étalonnage, les recommandations du Guide ISO/IEC 98-3:2008 [voir l'Article 2] doivent être suivies.

D'autres recommandations relatives à l'évaluation des **incertitudes** sont données à l'Annexe I.

7 Caractérisation du faisceau

7.1 Généralités

Le Tableau 1 donne des informations sur les paramètres acoustiques qui peuvent être utilisés pour spécifier l'émission acoustique des différents types d'appareils médicaux à ultrasons.