



BSI Standards Publication

Ultrasonics — Hydrophones

Part 2: Calibration for ultrasonic fields

National foreword

This British Standard is the UK implementation of EN IEC 62127-2:2025. It is identical to IEC 62127-2:2025. It supersedes BS EN 62127-2:2007+A2:2017, which will be withdrawn on 29 February 2028.

The UK participation in its preparation was entrusted to Technical Committee EPL/87, Ultrasonics.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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(IEC 62127-2:2025)

Ultrasons - Hydrophones - Partie 2: Etalonnage des champs ultrasoniques
(IEC 62127-2:2025)

Ultraschall - Hydrophone - Teil 2: Kalibrierung für Ultraschallfelder
(IEC 62127-2:2025)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

European foreword

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The following dates are fixed:

- latest date by which the document has to be implemented at national (dop) 2026-02-28 level by publication of an identical national standard or by endorsement
- latest date by which the national standards conflicting with the (dow) 2028-02-29 document have to be withdrawn

This document supersedes EN 62127-2:2007 and all of its amendments and corrigenda (if any).

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The text of the International Standard IEC 62127-2:2025 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61828:2020 NOTE Approved as EN IEC 61828:2021 (not modified)

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cencenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 61161	-	Ultrasonics - Power measurement - Radiation force balances and performance requirements	EN 61161	-
IEC 61689	-	Ultrasonics - Physiotherapy systems - Field specifications and methods of measurement in the frequency range 0,5 MHz to 5 MHz	EN IEC 61689	-
IEC 62127-1	-	Ultrasonics - Hydrophones - Part 1: Measurement and characterization of medical ultrasonic fields	EN IEC 62127-1	-
IEC 62127-3	2022	Ultrasonics - Hydrophones - Part 3: Properties of hydrophones for ultrasonic fields	EN IEC 62127-3	2023

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ULTRASONICS – HYDROPHONES –

Part 2: Calibration for ultrasonic fields

FOREWORD

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IEC 62127-2 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, Amendment 1:2013 and Amendment 2:2017. 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) directional response measurement and effective size determination procedures have been updated in 12.5.1 to align with recent changes in IEC 62127-3;

- d) Annex F has been amended to comprise a calibration technique for high-frequency complex-valued calibration;
- e) the reciprocity method description in Annex K was extended to also comprise focusing transducers;

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

Draft	Report on voting
87/878/FDIS	87/884/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/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 Terms in **bold** in the text are 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, or
- revised.

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INTRODUCTION

The spatial and temporal distribution of acoustic pressure in an ultrasonic field in a liquid medium is commonly determined using miniature ultrasonic **hydrophones**. These devices are not absolute measurement instruments and it is important that they are calibrated. This part of IEC 62127 specifies the calibration methods to use in determining the response of a **hydrophone** in the ultrasonic range, i.e. above 50 kHz. The main **hydrophone** application in this context lies in the measurement of ultrasonic fields emitted by medical diagnostic equipment in water. It is important to understand **hydrophone** behaviour over a wide frequency band in order to reliably characterize the acoustic parameters of the applied acoustic field. In particular, the frequency range above 15 MHz is important to fully characterize this equipment, primarily due to the increased appearance of high-frequency components in the ultrasonic signals, caused by nonlinear propagation. In addition, the number of medical ultrasonic systems that use frequencies above 15 MHz, particularly intra-operative probes, is growing. It has turned out in recent years that the **hydrophone** response below 0,5 MHz is also important in order to reliably determine the peak-negative (rarefactional) acoustic pressure.

While the term "**hydrophone**" can be used in a wider sense, it is understood here as referring to miniature piezoelectric **hydrophones**. It is this instrument type that is used today in various areas of medical ultrasonics and, in particular, to characterize quantitatively the field structure of medical diagnostic instruments [1]¹. With regard to other pressure sensor types, such as those based on fibre optics, some of the requirements of this document are applicable to these as well but others are not. If in the future these other "**hydrophone**" types gain more importance in field measurement practice, their characteristics and calibration will be dealt with in a future edition of IEC 62127-2 or in a separate part of IEC 62127.

NOTE 1 This document covers the ultrasonic frequency range, from 50 kHz to an upper frequency of 100 MHz. Not all techniques described are applicable to the full frequency range. Standards dealing with **hydrophone** properties (IEC 62127-3) and **hydrophone** use (IEC 62127-1) are being maintained in parallel. This will eventually lead to unified standards covering the whole field of practical **hydrophone** application.

NOTE 2 **Hydrophone** calibration in the lower ultrasonic and in the underwater sound frequency range is particularly addressed in the IEC 60565 series [2],[3].

¹ Numbers in square brackets refer to the Bibliography.

ULTRASONICS – HYDROPHONES –

Part 2: Calibration for ultrasonic fields

1 Scope

This part of IEC 62127 specifies:

- absolute **hydrophone** calibration methods;
- relative (comparative) **hydrophone** calibration methods.

Recommendations and references to accepted literature are made for the various relative and absolute calibration methods in the frequency range covered by this document.

This document is applicable to

- **hydrophones** used for measurements made in water and in the ultrasonic frequency range 50 kHz to 100 MHz;

NOTE 1 Although some physiotherapy medical applications of medical ultrasound are developing which operate in the frequency range 40 kHz to 100 kHz, the primary frequency range of diagnostic imaging remains above 2 MHz. It has recently been established that, even in the latter case, the **hydrophone** response at substantially lower frequencies can influence measurements made of key acoustic parameters [4].

NOTE 2 Calibration methods for underwater acoustics **hydrophones** applicable in the frequency range from 200 Hz to 1 MHz are available in IEC 60565-1 [2], and for frequencies from 0,01 Hz to several kilohertz in IEC 60565-2 [3].

- **hydrophones** employing piezoelectric sensor elements, designed to measure the pulsed wave and continuous wave ultrasonic fields generated by ultrasonic equipment;

NOTE 3 Some **hydrophones** can have non-circular active elements, arising from slight deviations from a circular structure caused, for example, by electrode structure; or, conversely, the active elements can actually be squares. It is important in these cases to pay special attention to the **directional response** and to the effective radii of the active element through various axes of rotation.

- **hydrophones** with or without a **hydrophone** pre-amplifier.

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 61161, *Ultrasonics – Power measurement – Radiation force balances and performance requirements*

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

IEC 62127-1, *Ultrasonics – Hydrophones – Part 1: Measurement and characterization of medical ultrasonic fields*

IEC 62127-3:2022, *Ultrasonics – Hydrophones – Part 3: Properties of hydrophones for ultrasonic fields*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62127-1, IEC 62127-3 and the following apply.

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

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

3.1

acoustic centre

point on or near a transducer from which the spherically divergent sound waves emitted by the transducer, and observable at remote points, appear to diverge

Note 1 to entry: This point is the boundary between the **near field** and the **far field**.

Note 2 to entry: In this region, the sound field has plane wave fronts changing to spherical wave fronts with divergence.

3.2

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 surface**

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 3 to entry: See IEC 62127-1:2022, Figure 1.

[SOURCE: IEC 62127-1:2022, 3.8, modified – In the definition, "aperture" has been replaced with "surface".]

3.3

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 62127-1:2022, 3.9]

3.4 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 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).

[SOURCE: IEC 62127-1:2022, 3.11]

3.5 beamwidth midpoint

linear average of the location of the centres of **beamwidths** in a plane

Note 1 to entry: The average is taken over as many **beamwidth** levels as given in IEC 61828:2020, Clause C.2 and Table C.2.

[SOURCE: IEC 61828:2020 [5], 3.22]

3.6 beam centre

point in a plane in the **far field**, usually perpendicular to the **beam axis**, at which the **spatial-peak temporal-peak acoustic pressure** occurs

3.7 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

$$I(t) = \frac{p(t)^2}{\rho c} \quad (1)$$

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/m²).

[SOURCE: IEC 62127-1:2022, 3.14]

3.8

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**.

[SOURCE: IEC 62127-1:2022, 3.15]

3.9

directional response

description of the response of a **hydrophone**, as a function of direction of propagation of the incident plane sound wave, in a specified plane through the **reference centre** and at a specified frequency

Note 1 to entry: Although **directional response** is a complex-valued function, it is generally the modulus of **directional response** that is of most interest and this is commonly presented graphically.

[SOURCE: IEC 62127-3:2022, 3.2]

3.10

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 the function of frequency. For representative experimental data, see [9].

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 half the greatest value of the length or width.

[SOURCE: IEC 62127-1:2022, 3.20]

3.11

effective radius of a non-focusing ultrasonic transducer

a_t

radius of a perfect disc piston-like ultrasonic source 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).

[SOURCE: IEC 62127-1:2022, 3.21]

3.12

effective wavelength

λ_{eff}

longitudinal speed of sound in the propagation medium divided by the acoustic-working frequency

Note 1 to entry: The **effective wavelength** is expressed in metres (m).

Note 2 to entry: Application dependent definitions of the acoustic-working frequency are given in IEC 62127-1:2022.

[SOURCE: IEC 61828:2020 [5], 3.46, modified – Note 2 to entry has been added.]

3.13**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 62127-1:2022, 3.22]

3.14**end-of-cable loaded sensitivity** $\underline{M}_L(f)$

<of a **hydrophone** or **hydrophone assembly**> quotient of the Fourier transformed **hydrophone** voltage-time signal $F(u_L(t))$ 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** $F(p(t))$ in the undisturbed **free field** of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_L(f) = \frac{F(u_L(t))}{F(p(t))} \quad (2)$$

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.

[SOURCE: IEC 62127-1:2022, 3.25]

3.15**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}

$$L_{M_L}(f) = 20 \log_{10} \frac{|\underline{M}_L(f)|}{M_{\text{ref}}} \text{ dB} \quad (3)$$

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

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

[SOURCE: IEC 62127-1:2022, 3.26]

3.16

end-of-cable open-circuit sensitivity

$\underline{M}_c(f)$

<of a **hydrophone**> quotient of the Fourier transformed **hydrophone** open-circuit voltage-time signal $F(u_c(t))$ at the end of any integral cable or output connector of a **hydrophone** to the Fourier transformed **acoustic pulse waveform** $F(p(t))$ in the undisturbed **free field** of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_c(f) = \frac{F(u_c(t))}{F(p(t))} \quad (4)$$

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.

[SOURCE: IEC 62127-1:2022, 3.27]

3.17

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

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.

Note 3 to entry: See IEC 61828:2020 [5], Figure B.5.

[SOURCE: IEC 61828:2020 [5], 3.52]

3.18

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 [5]).

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

[SOURCE: IEC 62127-1:2022, 3.30]

3.19

free field

sound field in a homogeneous and isotropic medium in which the effects of boundaries are negligible

[SOURCE: IEC 60565:2006, 3.13]

3.20**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 [6], 801-32-26]

3.21**hydrophone assembly**

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

[SOURCE: IEC 62127-3:2022, 3.13]

3.22**hydrophone axis**

nominal symmetry axis of the **hydrophone** active element

Note 1 to entry: Unless stated otherwise (explicitly and quantitatively) by the manufacturer, it is understood for the purposes of this document that this is given by the apparent geometrical symmetry axis of the **hydrophone**.

[SOURCE: IEC 62127-3:2022, 3.14]

3.23**hydrophone geometrical size**

geometrical size of a hydrophone active element

a_g

size defined by the lateral extents of the active element of a **hydrophone**

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

Note 2 to entry: For **hydrophones** with a circular geometry, the **hydrophone geometrical size** is a radius.

Note 3 to entry: For **hydrophones** with a rectangular geometry, the **hydrophone geometrical size** is a half the greater value of the length or width.

Note 4 to entry: For fibre optic **hydrophones**, the **hydrophone geometrical size** is the radius of the light spot at the tip of the fibre.

[SOURCE: IEC 62127-3:2022, 3.11, modified – Note 4 to entry has been added.]

3.24**hydrophone pre-amplifier**

active electronic device connected to, or intended 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** can 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 62127-3:2022, 3.15]

3.25**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 [7], 802-01-03, modified – Note 1 to entry has been added.]

3.26**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 surface** (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).

[SOURCE: IEC 62127-1:2022, 3.36]

3.27**longitudinal plane**

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

Note 1 to entry: See IEC 62127-1:2022, Figure 1.

[SOURCE: IEC 62127-1:2022, 3.39].

3.28**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.

[SOURCE: IEC 62127-1:2022, 3.41].

3.29**reference centre**

point on or near a **hydrophone** about which its acoustic receiving sensitivity is defined

Note 1 to entry: Unless stated otherwise (explicitly and quantitatively) by the manufacturer, it is understood for the purposes of this document that this is given by the geometrical centre of the front surface of the **hydrophone** active element.

[SOURCE: IEC 62127-3:2022, 3.16]

3.30**source aperture plane**

closest possible measurement plane to the **external transducer surface** plane that is perpendicular to the **beam axis**

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

Note 2 to entry: See Figure B.5, Figure B.7, Figure B.9 and Figure B.10 in IEC 61828:2020 [5].

[SOURCE: IEC 61828:2020 [5], 3.135].

3.31**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**

Note 1 to entry: See Figure B.5 and Figure B.6b in IEC 61828:2020 [5].

Note 2 to entry: **Source aperture width** is expressed in metres (m).

[SOURCE: IEC 61828:2020 [5], 3.136, modified – two Notes to entry on HITU transducers have been omitted.].

3.32**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

Note 1 to entry: See Figure 3 in IEC 62127-1:2022.

Note 2 to entry: **Transducer aperture width** is expressed in metres (m).

[SOURCE: IEC 62127-1:2022, 3.81].

3.33**transition distance**
 z_T

aperture area divided by π times the **effective wavelength** λ_{eff}

[SOURCE: IEC 61828:2020 [5], definition 3.153, modified – In the definition, the words "the **effective wavelength**" have been added and a subscript has been added to the symbol for **effective wavelength**.]

3.33.1**transition distance for design**
 z_{TD}

for a given **longitudinal plane**, the **transducer aperture area** A_{TA} of the **ultrasonic transducer** divided by π times the **effective wavelength** λ_{eff}

$$z_{TD} = A_{TA} / (\pi \lambda_{\text{eff}}) \quad (5)$$

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 $z_T = a_e^2 / \lambda_{\text{eff}}$.

Note 2 to entry: For a spherically focusing transducer, the **transition distance** is approximately the same but more exactly it is $z_T = 2D^2 \left(1 - \sqrt{1 - (a/D)^2} \right) / \lambda_{\text{eff}}$ 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 $z_{T1} = (L_{TA1})^2 / (\pi \lambda_{\text{eff}})$. The **transition distance** for the orthogonal **longitudinal plane** including the second **transducer aperture width** is $z_{T2} = (L_{TA2})^2 / (\pi \lambda_{\text{eff}})$.

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 : $z_T = \left(\frac{2}{\lambda} \right) \int_0^a W(r) r dr$

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

$$z_T = \left(\frac{4}{\pi \lambda_{\text{eff}}} \right) \left| \int_0^{L/2} W(x) dx \right|^2$$

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 $(\pi \lambda_{\text{eff}})$. 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 [5], 3.153.1, modified – A subscript has been added to the symbol for **effective wavelength** and Note 6 to entry has been omitted.]

3.33.2 transition distance for measurement

z_{TM}

for a given **longitudinal plane**, the **source aperture area**, A_{SAeff} , of the **ultrasonic transducer** divided by π times the **effective wavelength** λ_{eff}

$$z_{\text{TM}} = A_{\text{SAeff}} / (\pi \lambda_{\text{eff}}) \quad (6)$$

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

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

[SOURCE: IEC 61828:2020 [5], 3.153.2, modified – A subscript has been added to the symbol for **effective wavelength**.]

3.34 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 [10], 2.2.3.

3.35 wavelength

 λ

distance in the direction of propagation of a periodic wave between two successive positions at which the phase is the same

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

[SOURCE: IEC 60050-845:2020 [8], 845-21-025, modified – Notes 1, 2, 3, 5 and 6 to entry have been omitted. Note 4 to entry has been renumbered Note 1 to entry and "or decimal submultiples of metre" has been deleted.]

4 List of symbols

a_g	hydrophone geometrical size
a_h	effective hydrophone size
$a_{\max}$	maximum effective radius for a specific hydrophone application
a_P	lateral distance from the beam axis ($a_{P\max E}$, $a_{P\max H}$: maximum values with respect to avoiding edge wave and head wave interference, respectively)
a_t	effective radius of a non-focusing ultrasonic transducer
A_g	geometrical area of an ultrasonic transducer
B/A	Fox-Wallace nonlinearity parameter
c	speed of sound in a medium (usually water)
C_H	end-of-cable capacitance of the hydrophone including any integral cable and connector
d_1	distance between the auxiliary transducer and the reflector measured along the axis of symmetry
d_h	distance between the auxiliary transducer and the active element of the hydrophone measured along the axis of symmetry
d_m	distance between the auxiliary transducer and the last minimum of the acoustic pressure amplitude along the axis of symmetry of the auxiliary transducer
$D(\theta)$	normalized directional response function
e	base of natural logarithms
f	frequency
f_f	fundamental drive frequency of a signal used to generate nonlinear distortion
f_u	upper frequency limit of the stated frequency band of a hydrophone
F	geometric focal length of a focusing transducer
G_{th}	correction that accounts for the diffraction in the propagation field and is related to the waveform generation by the transducer and the reception by the hydrophone
G_{tt}	correction that accounts for the diffraction in the propagation field and is related to the generation and the reception by the transducer
i	imaginary unit
I_p	magnitude of the instantaneous intensity assuming proportionality with acoustic pressure squared
I_{sc}	current measured over a short circuit jumper replacing the transducer
I_t	transmitting current driven to a transducer

$\vec{I}(x,y,z,t)$	instantaneous intensity vector at the point (x,y,z) at time t
$I(x,y,z,t)$	component of the instantaneous intensity vector in the propagation direction at the point (x,y,z) at time t
$j_{\max}$	the number of the farthest scan point in a radial scan
J_p	reciprocity coefficient for plane waves
k	circular wave number ($= 2\pi/\lambda$)
L_{SA}	source aperture width
L_{TA}	transducer aperture width
$L_{M_L}(f)$	end-of-cable loaded sensitivity level
$L_{M_C}(f)$	end-of-cable open-circuit sensitivity level
$\underline{M}$	general symbol for the complex hydrophone sensitivity, $M = \underline{M} $ being its modulus and $\arg(\underline{M})$ being its argument ($=$ phase angle)
$\underline{M}_C(f)$	end-of-cable open-circuit sensitivity
$\underline{M}_L(f)$	end-of-cable loaded sensitivity
M_t^*	apparent receiving voltage response of an auxiliary transducer
N_{av}	number of waveform averages taken to generate a time-averaged voltage waveform
N	number of diametrical samples
N_{harm}	harmonic number
p_0	pressure amplitude
p_1	acoustic pressure amplitude at the face of a transducer
p_a	acoustic pressure generated by a transducer at its surface
p_i	acoustic pressure incident on a transducer surface
p_h	acoustic pressure incident on the hydrophone surface
$p(x,y,z,t)$	instantaneous acoustic pressure at the point (x,y,z) at time t
$P(l)$	total ultrasonic power passing through a plane of infinite extent in an acoustic field at a distance l from an ultrasonic transducer
P_o	total ultrasonic power emitted by a transducer
rf	radio-frequency signals
r	distance from the ultrasonic beam centre to a scan point
R	$(l\lambda / \pi a_1^2)$ normalized distance between a transducer and a hydrophone in terms of the Rayleigh distance $(\pi a_1^2 / \lambda)$
R_{RT}	amplitude reflection coefficient for the reflector–water interface
R_{1i}, R_{2i}	distances from the beam centre to the extremes of the i th diametrical beam scan
s	distance from the ultrasonic beam centre to the nearest scan point
S_t^*	apparent transmitting current response of an auxiliary transducer
t_H	arrival time of the nearest head wave
t_{TDS}	time available for a free field measurement in time delay spectrometry

T	acoustic transmission factor
$\underline{T}(f)$	complex-valued acoustic transmission factor in the frequency domain
U_{load}	voltage measured with the transducer coupled to the system
$U_L(x,y,z,t)$	end-of-cable voltage for a hydrophone with the hydrophone at the reference point (x,y,z) and at time t
$U_L'(x,y,z,t)$	end-of-cable voltage for a hydrophone including noise with the hydrophone at the reference point (x,y,z) and at time t
$U_n(x,y,z)$	root-mean-square (RMS) noise level measured with a hydrophone at the reference point (x,y,z)
U_t	voltage generated by a transducer in the receiving mode
U_T	voltage at the terminals of an ultrasonic transducer
$\vec{v}(x,y,z,t)$	Instantaneous particle velocity vector at the point (x,y,z) at time t
v_t	speed of a radial wave in a transducer plate
w_f	beamwidth of the fundamental-frequency field component
z	axial distance between a hydrophone and an ultrasonic transducer surface. (z_1 , z_2 , z_3 and z_4 are special distance values in accordance with certain criteria involving edge waves and head waves)
z_{min}	minimum distance for a finite size hydrophone from a transducer
z_{pf}	distance of the pressure focus from a focusing transducer
Z_{RT}	characteristic acoustic impedance of the reflector
z_T	transition distance
z_{TD}	transition distance for design
z_{TM}	transition distance for measurement
Δz	distance difference
Z_h	complex electric output impedance of a hydrophone
Z_L	complex electric load impedance
α	amplitude attenuation coefficient of plane waves in a medium (usually water)
β	nonlinearity parameter in the sense of $\beta = 1 + B/(2A)$
δ	amplitude of the second harmonic expressed as a percentage of the acoustic pressure at the fundamental frequency
δ_{av}	pressure amplitude correction for finite hydrophone size
θ	angle between the ultrasonic propagation direction and the z -axis, equivalent to the angle between the line joining the centre of the ultrasonic transducer and the centre of the hydrophone and the propagation direction
θ_1	angle between the line joining the centre of the ultrasonic transducer to the centre of the hydrophone and the direction of maximum sensitivity of the hydrophone
γ	ratio of beam radius to the effective hydrophone radius
ζ	acoustic displacement as measured by an optical interferometer
θ	angle of incidence of an ultrasonic wave with respect to the hydrophone axis
λ	wavelength
λ_{eff}	effective wavelength

λ_l	optical wavelength ; wavelength of light in vacuum
ζ	$\pi/2$ times the Rayleigh length (a_t^2/λ , see IEC 61828 [5]) of a focusing transducer
ρ	(mass) density of the measurement liquid (water)
ρc	characteristic acoustic impedance of the measurement liquid (water)
σ	nonlinear distortion parameter
σ_q	local distortion parameter
τ	pulse duration or burst duration ($\tau_{\max E}$, $\tau_{\max H}$: maximum values with respect to avoiding edge wave and head wave interference, respectively)
ω	circular frequency

5 Overview of calibration procedures

5.1 Principles

Hydrophones are required for absolute measurements of the properties of an acoustic field. The time-dependent voltage output from a **hydrophone**, $u(t)$, can be presented in the form:

$$u(t) = p(t) * m(t) \quad (7)$$

where

$p(t)$ is the pressure waveform;

$*$ is a convolution;

$m(t)$ is the impulse response of the **hydrophone**.

Viewed in the Fourier domain, if $\underline{U}(f)$, $\underline{P}(f)$ and $\underline{M}(f)$ are the respective Fourier transforms, then the resultant voltage spectrum, $\underline{U}(f)$, is equal to $\underline{P}(f) \times \underline{M}(f)$. The quantity $\underline{M}(f)$ is the **hydrophone** transfer function (sensitivity) and its complex value comprises both real and imaginary components.

In the past, ultrasonic **hydrophones** have been applied almost exclusively as amplitude sensors. A change has become apparent in recent years, and it is increasingly considered useful to have additional phase information. Some **hydrophone** calibration procedures have been extended to cover the determination of phase characteristics. IEC 62127-1:2022 partly relies on phase information for **hydrophones** within waveform deconvolution applications. However, the **hydrophone** measurement standard also provides a method for phase response retrieval from sensitivity modulus data as an alternative to phase response calibration. A summary of current capability for (relative) phase measurement is provided in Annex I and a method for full complex-valued calibration in F.2.3.2.

Procedures for the calibration of **hydrophones** are specified using the following principles:

a) calibration using a standard transducer.

A **hydrophone** can be calibrated by comparison with a standard transducer utilized as a source of ultrasonic power. The output power of the transducer shall be determined using radiation force balance techniques as given in IEC 61161;

b) calibration without using a standard transducer.

This type of calibration covers:

1) reciprocity calibration

A calibration based upon the reciprocity principle, in which at least one transducer is a reciprocal transducer;

2) physical calibration

A calibration in which the sound pressure at the **hydrophone** is calculated from the measurement of a physical parameter related to the acoustic field, such as acoustic displacement (e.g. optical interferometry).

NOTE "Absolute" **hydrophone** calibration is understood here in the sense of "without reference to another **hydrophone**". This is sometimes also referred to as "primary" calibration. On the other hand, **hydrophones** are often calibrated in practice following a "secondary" or "substitution" procedure, which means a sensitivity comparison with a calibrated reference **hydrophone**. The reference **hydrophone** itself can have been calibrated in "absolute" terms or against another reference **hydrophone**, and so on. Obviously, there are two different fundamental procedures: to perform an absolute **hydrophone** calibration and to compare the sensitivity of two **hydrophones**. Clause 9, Clause 10, and Clause 11, and Annex D, Annex F and Annex H deal with the former procedure. The latter procedure is dealt with in detail in Clause 12. Note that a substitution calibration usually involves both steps and that the user is expected to refer to both Clause 12 and the other clauses dealing with absolute calibration (and that **uncertainties** from both fundamental steps contribute to the final calibration **uncertainty** in the case of a substitution calibration).

5.2 Summary of calibration procedures

The appropriate frequency ranges of the various methods that can be used to calibrate ultrasonic **hydrophones** are given below, with a reference to the clause that specifies the relevant method. Table 1 provides a tabulation of the typical achievable calibration **uncertainty**.

a) **Free field** reciprocity calibration (Clause 9)

- Calibration without a standard transducer in a **free field**, between 50 kHz and 15 MHz.

b) **Free field** calibration by planar scanning (Clause 10)

- Calibration with a standard transducer in a **free field**, between 500 kHz and 15 MHz.

c) **Free field** calibration by optical interferometry (Clause 11)

- Physical calibration carried out through a **free field** measurement of the acoustic displacement, between 200 kHz and 100 MHz.

d) Calibration by comparison using a standard **hydrophone** (Clause 12)

- Calibration by comparison with a calibrated standard **hydrophone**, between 50 kHz and 40 MHz.

Table 1 – List of typical uncertainty values (for 95 % coverage) obtained by the calibration methods specified in this document and for the frequency range listed

Clause	Method	Frequency range	Uncertainty
9	Two-transducer reciprocity calibration (9.3.4)	1 MHz to 2 MHz	6 %
		up to 10 MHz	10 %
		up to 15 MHz	16 %
	Three-transducer reciprocity calibration (9.3.2)	50 kHz to 100 kHz	5 %
		up to 500 kHz	6 %
		up to 1 MHz	10 %
10	Free field calibration by planar scanning (Annex D)	500 kHz to 10 MHz	6 %
		up to 15 MHz	18 %
11	Free field calibration by optical interferometry (Annex F)	200 kHz ^a to 1 MHz	7 %
		up to 10 MHz	7 %
		up to 20 MHz	8 %
		up to 30 MHz	10 %
		up to 40 MHz	11 %
		up to 60 MHz	11 %
		up to 80 MHz	17 %
		up to 100 MHz	36 %
12	Calibration by comparison using a standard hydrophone (12.5.2) (Annex G, Annex H)	50 kHz to 200 kHz	9 %
		up to 1 MHz	8 %
		up to 10 MHz	7 %
		up to 20 MHz	11 %
		up to 30 MHz	12 %
		up to 40 MHz	12 %

^a The lower frequency range of 200 kHz should not be taken as the lower limit to which calibrations can be carried out using optical interferometry. This lower limit is typically controlled by reflections from the water tank walls, the device being calibrated, or other technical restrictions.

5.3 Reporting of results

The modulus of the end-of-cable sensitivity of the **hydrophone assembly** shall be stated in V/Pa or in decimal submultiples, or as a logarithmic level in dB with reference to a stated sensitivity value. It shall be stated whether the sensitivity value given is the **end-of-cable open-circuit sensitivity** or the **end-of-cable loaded sensitivity**. In the latter case, the relevant electrical loading conditions shall be stated, i.e. the **electric load impedance**, in order to obtain the stated sensitivity.

The phase of the end-of-cable sensitivity can be given as a function of frequency as a list of values and, in addition, graphically.

NOTE 1 "End-of-cable" refers to the end of the output cable of the **hydrophone assembly**, with or without a **hydrophone pre-amplifier**.

The **uncertainty** of the stated sensitivity shall be given. If the sensitivity is given for a frequency interval, then the **uncertainty** shall be given for exactly the same interval. If the sensitivity is given for a number of frequency points, then the **uncertainty** should be given for frequency intervals that are likely to be useful to the user.

NOTE 2 Guidance on the assessment of **uncertainty** can be found in Annex A.

The frequency interval over which the sensitivity is given and over which the **uncertainty** applies shall be stated. For the purposes of this document, sensitivity and **uncertainty** values can be given separately for several frequency intervals. The frequency response can be given in terms of absolute sensitivity values or in a relative representation, relative with reference to the absolute **hydrophone** sensitivity at a certain frequency. In the case of the relative representation, the reference sensitivity and the frequency to which it applies shall be stated.

The methods by which the sensitivity and its **uncertainty** have been obtained shall be described.

Any calibration is only valid for the environmental conditions existing during the calibration. The environmental conditions pertaining to that calibration shall therefore be stated. These shall include all those conditions that can influence the sensitivity of the test device. Conditions to be reported shall include:

- date of the calibration;
- water temperature and its **uncertainty**;
- whether or not a **hydrophone pre-amplifier** is included in the **hydrophone assembly**, including unique identification information;
- water properties, length of soaking time and any wetting procedure adopted, such as the addition of a wetting agent;

NOTE 3 The sensitivity of single-layer, electrically unshielded membrane **hydrophones**, for example is affected by the electrical conductivity of the water used.

NOTE 4 The response of some **hydrophones** can change during immersion in water, and it is important that the calibrations have been completed only following sufficient soaking such that response has stabilized.

- the orientation of the **hydrophone** about any axis or alignment mark presented on its body or casing;
- in situations where the mounting arrangement affects the sensitivity of a **hydrophone**, the details of the mount shall be specified;

NOTE 5 It is important to take care in designing the **hydrophone** mount at low frequencies (below 200 kHz) where the acoustic **wavelengths** are sufficiently large that the use of long-bursts can lead to the direct acoustic signal being contaminated by reflections from the mount. The importance of the effect can be investigated through varying the burst length and observing the influence of reflections on the **hydrophone** signal. Acoustic absorbers can be useful in suppressing these reflections. **Hydrophone** sensitivity can also be affected by the way the **hydrophone** is clamped, and again this can be evaluated by systematically investigating the various configurations. Also, for some probe and needle-type **hydrophones**, depending on the construction geometry, internal reverberations can be present but arrive only after a significant delay. Therefore, it is important to ensure that the insonation conditions pertaining to the **hydrophone** calibration are appropriate for its subsequent application [11].

- a specification of the characteristics of any additional cables attached to the **hydrophone**, during the calibration;
- the nominal direction of ultrasonic incidence in relation to the **hydrophone**;

NOTE 6 This is important, as it has been found in the literature [12] that even with membrane **hydrophones**, the response can change upon reversal of the ultrasonic propagation direction in relation to the **hydrophone**.

- the maximum acoustic pressure experienced by the **hydrophone** during the calibration;

NOTE 7 Annex B describes the linearity of **hydrophones** manufactured from polyvinylidene fluoride (PVDF) for use in characterizing high amplitude acoustic fields.

- any assumptions made about the device under test (e.g. the position of the **hydrophone reference centre**).

If use is made of a calibrated **hydrophone** in an environment significantly different from that which existed during calibration, the user can be obliged to increase his or her assessment of measurement uncertainties to account for the change in environment.

5.4 Recommended calibration periods

The recommended calibration period for the **hydrophone** will depend on its characteristics. This interval shall be specified by the manufacturer.

NOTE 1 A calibration period of one year will be appropriate in most cases (see IEC 62127-3).

For reference **hydrophones**, which are used purely for calibration purposes, it is recommended that a calibration is performed annually. Where **hydrophones** are used in the field, calibrations can be required at shorter time intervals.

NOTE 2 It can be useful to check the calibration of a working (or field) **hydrophone** through a "spot check" comparison with a second calibrated (reference) **hydrophone** or a check source, using one of the waveform concepts described in Annex G. In extreme cases, where there are concerns regarding the stability of a working **hydrophone**, this can be undertaken before and after measurements (see **hydrophone** use in IEC 62127-1).

6 Generic requirements of a hydrophone calibration system

6.1 Mechanical positioning

6.1.1 General

Precise positioning and orientation of the transducer, **hydrophone** and reflector (for the reciprocity method specified in Clause 9) is needed and these components should be mounted in stable, rigid supports which allow the appropriate adjustments to be made. It is recommended that the **hydrophone** and transducer are equipped with a means of setting their lateral positions and orientation such that the change in the **hydrophone** output signal is less than 0,1 dB if the mounts controlling either the spatial position or the relative orientation of the **hydrophone** are moved by one incremental step.

6.1.2 Accuracy of the axial hydrophone position

The axial distance of the **hydrophone reference centre** from the transducer shall be known and reproducible to within 0,2 mm.

NOTE 1 In order to derive the calibration **uncertainty**, repeat measurements can be made that can involve the removal and replacement of the **hydrophone** at the same position in the transducer field.

NOTE 2 The distance of the **hydrophone** from the transducer can be estimated from a knowledge of the time elapsed between the electrical excitation applied to the transducer and the arrival time of the acoustic wave at the **hydrophone**, through a knowledge of the speed of sound in water at that particular temperature.

This requirement will possibly need modification in the case of focusing source transducers, dependent on their actual axial field distribution.

NOTE 3 For focusing source transducers operating in the frequency range of this document, positioning is critical. The following is an assessment of the axial distance change from the focal length, i.e. $\Delta z = F - z$, leading to a pressure reduction of 1 dB. Starting from the theoretical formula $\sin[\xi(1/z - 1/F)] / [\xi(1/z - 1/F)] = 0,89$, where

$$\xi = \pi a_t^2 f / (2c), \text{ a two-term sine expansion yields } \Delta z = 0,808 F^2 / \xi.$$

NOTE 4 In the following example, if a plane ultrasonic wave in the linear amplitude range is propagated at a water temperature of 22 °C, the ultrasonic amplitudes at two axial positions that are 2 mm apart differ by 0,09 dB for a frequency of 15 MHz and by 0,7 dB for a frequency of 40 MHz, as a consequence of the frequency-dependent attenuation (see Annex E).

6.1.3 Accuracy of the lateral hydrophone position

The variation of the **hydrophone** output voltage should be checked when the lateral **hydrophone** position is changed to ensure that the signal is maximized. The condition for the lateral **hydrophone** position is that the output signal shall not be reduced by more than 0,5 dB from the maximum value.

NOTE In the **far field** of a theoretical, plane circular piston source and in the focal plane of a theoretical, focusing transducer under linear propagation conditions, the lateral distance from the field axis is $r = 0,107 \cdot c \cdot z / (f \cdot a_t)$ for a 0,5 dB amplitude reduction and $r = 0,151 \cdot c \cdot z / (f \cdot a_t)$ for a 1 dB amplitude reduction.

6.2 Temperature measurements and temperature stability

The electroacoustic properties of **hydrophones** vary with ambient temperature. For this reason, it is recommended that wherever possible, the **hydrophone** is calibrated under the same conditions of temperature as those under which it will be used. If this is not possible, then corrections to **hydrophone** sensitivity and frequency response values can be applied based on earlier calibrations or validated analytical models. The corrected **hydrophone** sensitivity and response values should have lower **uncertainty** than the uncorrected values.

Temperature drifts are to be avoided for two reasons:

- a) the amplitude of the ultrasonic wave arriving at the **hydrophone** depends on the temperature, as a consequence of the temperature-dependent ultrasonic attenuation in water (see Annex E);
- b) the time-of-flight of the ultrasonic signal depends on the temperature, as a consequence of the temperature-dependent speed of sound in water (see Annex E, Table E.1). This is of relevance to the adjustment of the time gate for bursts or pulses and also to time delay spectrometry.

With respect to a), the following example can be given. If a plane ultrasonic wave in the linear amplitude range is propagated over 15 cm at a temperature of approximately 22 °C, the resulting ultrasonic amplitude differs for two temperatures that are 1 °C apart by 0,2 dB at a frequency of 15 MHz and by 1,5 dB at a frequency of 40 MHz. (The attenuation coefficient in water is proportional to the square of the frequency. Values as a function of temperature are given in Annex E).

With respect to b), the following recommendation can be made: in a measurement of Type II specified in Clause 12 (comparison of sensitivity of two or more **hydrophones**), the axial **hydrophone** distance should be adjusted to a constant propagation time.

6.3 Hydrophone size

The active element of a **hydrophone** generates a voltage across its electrodes proportional to the average acoustic pressure over its surface. If full spatial resolution is to be achieved, therefore, the **effective hydrophone size** shall be small compared with the **wavelength** of the highest frequency component within the acoustic field used for calibration. Furthermore, the actual acoustic pressure on the **hydrophone's** sensitive surface is influenced by diffraction of the **hydrophone** itself [9],[13],[14].

NOTE 1 If the **hydrophone** is carefully designed to have a known or well-defined active surface, it is possible to remove the effects of spatial averaging and diffraction from the data, at a given frequency, by deconvolution, based on the known dimensions of the active element.

NOTE 2 Guidance in assessing the influence of spatial averaging on calibrations can be found in IEC 62127-1 and Annex J.

6.4 Measurement vessel and water properties

The test tank shall be sufficiently large to allow the establishment of **free field** conditions at the lowest frequency of interest. It should also be large enough to allow the transducer–**hydrophone** separation to be varied to a degree consistent with the requirements of the applied calibration technique.

The walls of the tank and water surface should be at a sufficient distance from the transducer and **hydrophone** to ensure that any signal resulting from reflections at these surfaces will not interfere with the first signal arrival generated by the transducer. Furthermore, where possible, such surfaces should be lined with acoustically absorbent materials.

It is important that the acoustic signal is not contaminated by reflections. The following check is recommended at the beginning of each measurement. In all cases where bursts or pulses are applied, the **hydrophone** output signal should be observed when the transducer–**hydrophone** distance is varied over several millimetres, in order to ensure the absence of multiple transducer–**hydrophone** echoes from the signal received. If such echoes interfere with the signal received, a remedy can be to change the pulse repetition frequency.

The water properties shall be consistent with the specification provided by the **hydrophone** manufacturer.

NOTE The sensitivity of some **hydrophones** can be dependent on the electrical conductivity of the water medium. In such cases, it is important to take care to ensure that the conditions for the measurement are sufficiently similar to those of the calibration.

6.5 Measurement of output voltage

The signal from the **hydrophone** or **hydrophone pre-amplifier** and any transducer shall be measured with the aid of an oscilloscope, digital signal analyser, spectrum analyser or other appropriate instrument with sufficient bandwidth and sensitivity. Additional amplification of the signal from the **hydrophone** or **hydrophone pre-amplifier** will possibly also be necessary in order to achieve acceptable signal-to-noise.

The instrument to which the **hydrophone** or **integral amplifier** is connected (e.g. oscilloscope, digital signal analyser, spectrum analyser, amplifier) shall meet the following requirements:

- its complex input impedance over the relevant frequency range of interest shall be known so that the **end-of-cable loaded sensitivity** can be determined (see Annex C);
- its linearity with the input signal over a dynamic range of 50 dB shall be better than $\pm 0,3$ dB;
- in the case of a digital signal analyser: for recording temporal waveforms, the sampling rate shall be at least $5f$ samples per second, where f is in hertz. Antialiasing precautions should be considered if appropriate. Also, the gain shall be adjusted to allow at least seven significant bits in the digitized waveform.

NOTE For an upper frequency limit of 100 MHz, for example, it is important that the sampling rate is at least 500 million samples per second.

7 Electrical considerations

7.1 Signal type

The signal used for the calibration can be either broadband pulse, swept sinusoidal [15] or pulsed sine wave (gated tone-burst). A sufficient number of frequencies shall be chosen to ensure that the **hydrophone** performance is well-characterized over the desired frequency range.

NOTE The various possible waveform concepts that can be used to obtain **hydrophone** calibration information over the frequency range of interest are summarized in Annex G.

7.2 Earthing

In order to avoid earth loops, the electrical terminals of the transducers should be kept free from contact with the water. Exposed metal parts of one **hydrophone** shall be the only earth connection for the cable screen of the **hydrophone** and for the **hydrophone** amplifier. All other earth contacts shall be excluded.

NOTE This condition can be relaxed when a tone burst is used such that the acoustic signal arrives at the **hydrophone** after the electrical excitation is completed.

7.3 Measurement of hydrophone output voltage

7.3.1 General

The open-circuit voltage of the **hydrophone** shall be determined at the end of the **hydrophone** cable.

For a continuous wave signal, the measurement can be done using a high impedance voltmeter. However, for tone-burst signals, it is best accomplished by digitizing the **hydrophone** voltage waveform, for example using a digitizing oscilloscope or a computer-based analogue-to-digital converter. Where an amplifier, attenuator or filter are used in combination with the voltmeter or digitizer to form a measuring channel, these elements will generally also require calibration.

NOTE Continuous wave signals relevant to **hydrophone** calibration techniques are described in Annex H. Amplitude-modulated waveform concepts are described in Annex G.

7.3.2 Electrical loading by measuring instrument

During the measurements, the **hydrophone** shall be connected to a high input impedance measuring instrument (amplifier, voltmeter, oscilloscope or digitizer). Where the impedance of the **hydrophone** is high (for example for a small piezoelectric **hydrophone** of low capacitance), consideration shall be given to the electrical loading of the **hydrophone** by the measuring instrument. In such cases, electrical loading corrections shall be applied to the measured voltage to obtain the open-circuit voltage. The corrections can be calculated using the procedure given in Annex C. If the same electrical load is used throughout the calibration for a particular **hydrophone**, then corrections can be applied to the sensitivity rather than to the individual measured voltages.

NOTE 1 If, in a practical application, the **hydrophone** is used with subsequent electronic components such as amplifier, oscilloscope, etc., the frequency response of the whole system is, of course, influenced also by the frequency response of these additional components.

NOTE 2 It is important to pay attention to the appropriateness of the output impedance of the **hydrophone** or amplifier in relation to the input impedance of the connected measuring instrument.

7.3.3 Electrical loading by extension cables

If an extension cable is attached to the **hydrophone**, this cable will electrically load the **hydrophone** and corrections shall be applied to obtain the open-circuit end-of-cable **hydrophone** voltage. Where the cable and **hydrophone** appear electrically to be purely capacitances (this is generally true for a cable and is true for a **hydrophone** in the frequency range well below resonance), a correction can be derived from the capacitances of the **hydrophone** and cable. Where the impedance of the **hydrophone** is not purely capacitive (for example at frequencies close to resonance), the complex impedance shall be used to calculate the loading correction. Guidance on both the above cases is given in Annex C. If the same extension cable is used throughout the calibration for a particular **hydrophone**, the corrections can be applied to the sensitivity rather than to the individual measured voltages.

NOTE To reduce the impact of electrical loading, some **hydrophones** are provided with a **hydrophone pre-amplifier** that is typically mounted as close to the **hydrophone** as possible (see 7.3.6). This is particularly important, at high frequencies, as a means of reducing the effect of cable resonances.

7.3.4 Noise

The level of electrical noise can degrade the accuracy with which electrical measurements can be made. The signal-to-noise ratio shall be sufficient such that measurements can be made without significant loss of accuracy. The signal amplitude should be at least 20 dB greater than the noise level.

NOTE 1 The level of broadband interfering noise can be reduced by the use of a band-pass filter with a bandwidth sufficiently wide to allow the signal to pass through without distortion.

NOTE 2 In the presence of electrical noise, the signal-to-noise ratio can be improved by the averaging of repeated signals. For random noise, averaging N_{av} signals will improve the signal-to-noise ratio by a factor of the square root of N_{av} .

7.3.5 Cross-talk (radio-frequency rf pick-up) and acoustic interference

In the presence of interference and cross-talk, signal-averaging and narrow-band filtering will not in general lead to an improvement. Efforts should be made to determine the cause of the problem and steps taken to minimize the effects. The acoustic interference level shall be at least 30 dB lower than the signal level.

Where cross-talk is present with tone-burst signals, care should be taken if the length of the burst is greater than the acoustic propagation delay.

NOTE 1 In these situations, cross-talk will contaminate the direct acoustic signal. The effect can be evaluated through varying the tone-burst length and observing any consequent changes in the **hydrophone** waveform using an oscilloscope.

In the case of a continuous wave signal, the cross-talk level shall be at least 40 dB lower than the signal level.

NOTE 2 The level of rf pick-up or cross-talk can be estimated by placing an extremely acoustically attenuating (but thin) layer of material (such as expanded polystyrene) directly between the transducer and the **hydrophone**. This will completely extinguish the acoustic signal, leaving the signal due to the pick-up.

7.3.6 Integral hydrophone pre-amplifiers

Where a **hydrophone** has an integral **hydrophone pre-amplifier**, the sensitivity can be expressed as end-of-cable sensitivity (including the performance of the **hydrophone pre-amplifier**). Where a **hydrophone** has an integral **hydrophone pre-amplifier**, corrections for electrical loading by extension cables or measuring instruments are unnecessary.

8 Preparation of hydrophones

8.1 General

Prior to the actual calibration procedure, careful preparation of the **hydrophones** is necessary, as outlined in 8.2 to 8.4.

8.2 Wetting

The user shall ensure that the **hydrophone** is wetted properly and that all air bubbles are removed from the **hydrophone** and faces taking active part in the calibration. After measurements are completed, the active faces shall again be inspected, and the measurements shall be discarded if any air bubbles are found.

8.3 Hydrophone support

The ideal supporting mount for a **hydrophone** shall cause minimal influence on the measured sensitivity. However, some **hydrophones** are more susceptible than others to the influence of the method of mounting.