



BSI Standards Publication

Ultrasonics – Hydrophones

Part 2: Calibration for ultrasonic fields up to 40 MHz (IEC 62127-2:2007)

National foreword

This British Standard is the UK implementation of EN 62127-2:2007, incorporating amendment A1:2013 and including amendment A2:2017. It is identical to IEC 62127-2:2007, incorporating amendment 1:2013 and including amendment 2:2017. It supersedes BS EN 62127-2:2007+A1:2013, which is withdrawn.

The start and finish of text introduced or altered by amendment is indicated in the text by tags. Tags indicating changes to IEC text carry the number of the IEC amendment. For example, text altered by IEC amendment A1 is indicated by A1 A1.

The text of IEC amendment 2:2017 has been provided in its entirety at the beginning of this document. BSI's policy of providing consolidated content remains unchanged; however, in the interest of expediency, in this instance BSI have chosen to collate the relevant content at the beginning of this document.

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 secretary.

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Amendments/corrigenda issued since publication

Date	Text affected
31 July 2013	Implementation of IEC amendment 1:2013 with CENELEC endorsement A1:2013: Annex ZA updated
31 March 2018	Implementation of IEC amendment 2:2017 with CENELEC endorsement A2:2017

English version

**Ultrasonics -
Hydrophones -
Part 2: Calibration for ultrasonic fields up to 40 MHz
(IEC 62127-2:2007)**

Ultrasons -
Hydrophones -
Partie 2: Etalonnage pour les champs
ultrasonores jusqu'à 40 Mhz
(CEI 62127-2:2007)

Ultraschall -
Hydrophone -
Teil 2: Kalibrierung für Ultraschallfelder
bis zu 40 MHz
(IEC 62127-2:2007)

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

Central Secretariat: rue de Stassart 35, B - 1050 Brussels

Foreword

The text of document 87/353/CDV, future edition 1 of IEC 62127-2, prepared by IEC TC 87, Ultrasonics, was submitted to the IEC-CENELEC parallel Unique Acceptance Procedure and was approved by CENELEC as EN 62127-2 on 2007-09-01.

EN 62127-1, EN 62127-2 and EN 62127-3 are being published simultaneously. Together these European Standards cancel and replace EN 61101:1993, EN 61102:1993 + A1:1994, EN 61220:1995 and EN 62092:2001.

The following dates were fixed:

- latest date by which the EN has to be implemented
at national level by publication of an identical
national standard or by endorsement (dop) 2008-06-01
- latest date by which the national standards conflicting
with the EN have to be withdrawn (dow) 2010-09-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 62127-2:2007 was approved by CENELEC as a European Standard without any modification.

**Ultrasonics - Hydrophones -
Part 2: Calibration for ultrasonic fields up to 40 MHz
(IEC 62127-2:2007/A1:2013)**

Ultrasons - Hydrophones -
Partie 2: Etalonnage des champs
ultrasoniques jusqu'à 40 Mhz
(CEI 62127-2:2007/A1:2013)

Ultraschall - Hydrophone -
Teil 2: Kalibrierung für Ultraschallfelder
bis zu 40 MHz
(IEC 62127-2:2007/A1:2013)

This amendment A1 modifies the European Standard EN 62127-2:2007; it was approved by CENELEC on 2013-03-15. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this amendment the status of a national standard without any alteration.

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

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Foreword

The text of document 87/519/FDIS, future amendment 1 to edition 1 of IEC 62127-2, prepared by IEC/TC 87 "Ultrasonics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62127-2:2007/A1:2013.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2013-12-15
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2016-03-15

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

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The text of the International Standard IEC 62127-2:2007/A1:2013 was approved by CENELEC as a European Standard without any modification.

English Version

Ultrasonics - Hydrophones - Part 2: Calibration for ultrasonic
fields up to 40 MHz
(IEC 62127-2:2007/A2:2017)

Ultrasons - Hydrophones - Partie 2: Etalonnage des
champs ultrasoniques jusqu'à 40 Mhz
(IEC 62127-2:2007/A2:2017)

Ultraschall - Hydrophone - Teil 2: Kalibrierung für
Ultraschallfelder bis zu 40 MHz
(IEC 62127-2:2007/A2:2017)

This amendment A2 modifies the European Standard EN 62127-2:2007; it was approved by CENELEC on 2017-04-26. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this amendment the status of a national standard without any alteration.

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European foreword

The text of document 87/612/CDV, future IEC 62127-2:2007/A2, prepared by IEC/TC 87 "Ultrasonics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62127-2:2007/A2:2017.

The following dates are fixed:

- latest date by which the document has to be (dop) 2018-01-26
implemented at national level by
publication of an identical national
standard or by endorsement
- latest date by which the national (dow) 2020-04-26
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Endorsement notice

The text of the International Standard IEC 62127-2:2007/A2:2017 was approved by CENELEC as a European Standard without any modification.

Annex ZA
(normative)

**Normative references to international publications
with their corresponding European publications**

The following referenced documents are indispensable for the application 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 When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60050-801	-	International Electrotechnical Vocabulary (IEV) - Chapter 801: Acoustics and electroacoustics	-	-
IEC 60565	- ¹⁾	Underwater acoustics - Hydrophones - Calibration in the frequency range 0,01 Hz to 1 MHz	EN 60565	2007 ²⁾
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 61689	-
IEC 61828	-	Ultrasonics - Focusing transducers - Definitions and measurement methods for the transmitted fields	EN 61828	-
IEC 62127-1 + corr. August + A1	2007 2008 2013	Ultrasonics - Hydrophones - Part 1: Measurement and characterization of medical ultrasonic fields up to 40 MHz	EN 62127-1 + A1	2007 2013
IEC 62127-3	- ¹⁾	Ultrasonics - Hydrophones - Part 3: Properties of hydrophones for ultrasonic fields up to 40 MHz	EN 62127-3	2007 ²⁾

INTERNATIONAL STANDARD

NORME INTERNATIONALE

AMENDMENT 2
AMENDEMENT 2

**Ultrasonics – Hydrophones –
Part 2: Calibration for ultrasonic fields up to 40 MHz**

**Ultrasons – Hydrophones –
Partie 2: Etalonnage des champs ultrasoniques jusqu'à 40 MHz**

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FOREWORD

This amendment has been prepared by IEC technical committee 87: Ultrasonics.

The text of this amendment is based on the following documents:

CDV	Report on voting
87/612/CDV	87/639/RVC

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

The committee has decided that the contents of this amendment and the base publication will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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

2 Normative references

Add the following new reference:

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

3 Terms, definitions and symbols

3.26

derived instantaneous intensity

(added by Amendment 1)

Delete the following text below the term:

"approximation of the **instantaneous intensity**"

Replace the existing four lines before Equation (1) by the following:

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

4 List of symbols

Replace:

ρc specific acoustic impedance

by

ρc characteristic acoustic impedance of the measurement liquid (water)

Add the following new symbols:

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

R_{RT} amplitude reflection coefficient for the reflector/water interface

Z_{RT} characteristic acoustic impedance of the reflector

J_p reciprocity coefficient for plane waves

S_t^* apparent transmitting current response of an auxiliary transducer

M_t^* apparent receiving voltage response of an auxiliary 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

I_t transmitting current driven to a transducer

U_t voltage generated by a transducer in the receiving mode

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

U_{load} voltage measured with the transducer coupled to the system

I_{sc} current measured over a short circuit jumper replacing the transducer

9 Free field reciprocity calibration

9.1 General

Replace the existing text by the following:

This clause specifies the primary reference measurement procedure (see JCGM 200:2012, 2.8 [79]) calibration of **hydrophones** under **free field** conditions using the principle of reciprocity.

Add the following new note:

NOTE The free field condition can be achieved in a confined water space by following any of a variety of measurement procedures, such as with the use of tone-burst (time-gated sine wave – see 10.5.3), time-delay spectrometry [63, 68], frequency modulated chirp [80, 81] or other techniques [82].

9.4 Two-transducer reciprocity calibration method

9.4.1 Apparatus

Replace the existing subclause title and text by the following:

9.4.1 Auxiliary transducers

Circularly plane piston auxiliary transducers should be used to generate the ultrasonic field in the frequency range of interest, limited to the maximum range between 1 MHz and 15 MHz. The effective radiation area (A_{ER}) shall be determined, according to IEC 61689, for each transducer and at all frequencies the transducer is intended to be used. If a frequency modulated chirp is to be used as excitation signal, the A_{ER} shall be determined at least in the minimum, maximum and one intermediate frequency in the range of interest.

The position of the last minimum of acoustic pressure amplitude along the axis of symmetry, d_m , shall be determined with an uncertainty not larger than 1 mm. It shall be done as an on-axis line scan, according to IEC 61689, at the same frequencies the A_{ER} was determined. The near field distance produced by the auxiliary transducer is defined as $N_1 = a_t^2/\lambda$, where λ is the ultrasonic wavelength in water at the frequency of operation and $a_t = \sqrt{2\lambda d_m + \lambda^2}$ is the effective radius of the ultrasonic transducer.

NOTE Focusing auxiliary transducers can be used, but several corrections need to be applied, and this document is only intended for plane-piston transducers. A detailed implementation of a reciprocity-based calibration method using focusing transducers can be found in [84].

The effective radiation area (A_{ER}) is used in the equations of Annex K to properly assess the diffraction correction and the reciprocity coefficient for plane waves, whilst the last minimum of pressure amplitude along the axis of symmetry (d_m) is used to indirectly define the near field distance (N_1), being $N_1 = (2\lambda d_m + \lambda^2)/\lambda$. Although both quantities A_{ER} and d_m are directly linked for ideal transducers, both shall be determined experimentally according to IEC 61689.

9.4.2 Procedure

Replace the existing subclause title and text by the following:

9.4.2 Reflector

The reflector should comprise a flat surface whose smallest linear dimension shall be at least four times the effective radius of the ultrasonic transducer a_t . The reflector shall also be flat to $\pm 10 \mu\text{m}$, with a surface finish good to $\pm 5 \mu\text{m}$ (surface roughness: $R_v < 5 \mu\text{m}$; $R_p < 5 \mu\text{m}$; $R_a < 1 \mu\text{m}$). The thickness of the reflector shall be such that the first reflection from the rear surface will not interfere with that directly from the front surface for any of the excitation signals to be used. Special attention shall be given for long burst or low-rate frequency modulated chirps, mainly at the lowest frequencies of interest.

The amplitude reflection coefficient for the reflector/water interface R_{RT} shall be experimentally determined, for instance by the relation $R_{RT} = (Z_{RT} - \rho c)/(Z_{RT} + \rho c)$, where ρc is the characteristic acoustic impedance of the water and Z_{RT} is the characteristic acoustic impedance of the reflector.

NOTE R_v is the maximum valley depth, R_p is the maximum peak height and R_a is the arithmetic average describing the reflector profile roughness amplitude parameters.

Add the following new subclauses:

9.4.3 Measurement field

As both the auxiliary transducer and the **hydrophone** have finite apertures, a diffraction pattern is present in the ultrasonic field. To minimize uncertainties due to the aperture

numerical corrections to be applied to the measurement quantities, the nearest measurement shall be performed at least at $0,9 \times N_1$, and the furthest distance shall not be larger than $2,2 \times N_1$. Water-air surface and tank walls shall be far enough from the ultrasonic path such that any reflected waveform will not interfere with the direct waveform at the measurement spot.

If any structure is too close to the direct ultrasonic waveform path, it shall be covered with absorbing lining to minimize the interference with the measurement signal, and concern about that interference shall be included in the uncertainty budget.

9.4.4 Reciprocity approach

Reciprocity can be established as a primary **hydrophone** calibration method provided some practical and theoretical details are adopted. Annex K depicts the fundamentals of the reciprocity approach.

9.4.5 Measurement procedure

Several distinct setups (see Annex K [83, 84, 85]) could be used regarding the positioning of the three main elements of the two-transducer reciprocity calibration method: auxiliary transducer, reflector and **hydrophone**.

Regardless of the configuration adopted, the self-calibration of the auxiliary transducer is the first step, and it is done to quantify the acoustic pressure generated by the transducer in a defined spot in the ultrasonic field.

Annex K (informative)

Two-transducer reciprocity calibration method

Replace the existing Annex K, added by Amendment 1, by the following:

K.1 General

The two-transducer reciprocity method involves the assessment of the acoustic pressure in a defined spot in the ultrasonic field. To accomplish that, the first step is to assess the ultrasonic field generated by an auxiliary transducer. The second step is to place the active element of the **hydrophone** to be calibrated in a defined spot for which the acoustic pressure can be defined as precisely as possible.

K.2 Fundamentals of reciprocity

A reversible transducer has an apparent transmitting current response $S_t^*(\omega)$ and apparent receiving voltage response $M_t^*(\omega)$ defined as

$$S_t^* = \frac{p_0(\omega)}{I_t(\omega)} \quad \text{and} \quad M_t^* = \frac{U_t(\omega)}{p_i(\omega)} \quad (\text{K.1})$$

where p_0 is the acoustic pressure generated by the auxiliary transducer at its surface, I_t is the transmitting current of the transducer, p_i is the acoustic pressure incident on the transducer surface and U_t is the voltage generated by the transducer in the receiving mode.

NOTE The term 'acoustic pressure' is used in Annex K, although it is recognized that in any practical situation this quantity will vary spatially. Similarly, the electrical output of transducer devices used in reception mode will be dependent on the acoustic pressure spatially-averaged on their active surface.

If the transducer is reciprocal, the reciprocity coefficient for plane waves J_p relates $S_t^*(\omega)$ and $M_t^*(\omega)$ as follows:

$$J_p = \frac{M_t^*(\omega)}{S_t^*(\omega)} \quad (\text{K.2})$$

By definition, $J_p = \frac{2A_{ER}}{\rho c} I_p = \frac{2A_{ER}}{\rho c}$.

If the wave generated by a reciprocal transducer propagates in water and reflects off with a normal incidence at a reflector distant d_1 from the transducer surface placed on its axis of symmetry, it produces an incident wave whose acoustic pressure can be measured by the reciprocal transducer. Relating the definition by Equation (K.3)

$$p_i(\omega) = p_0(\omega) R_{RT} e^{-2\alpha d_1} G_{tt} \quad (\text{K.3})$$

where α is the amplitude attenuation coefficient of plane waves in water and G_{tt} is the correction due to the fact that the returning waveform is generated and measured by a finite transducer, i.e. it accounts for the diffraction in the propagation field and is related to the generation and reception by the transducer. Combining Equations (K.1), (K.2) and (K.3), the

acoustic pressure generated by a reciprocal transducer at its surface is related to electrical and geometrical quantities as follows:

$$p_0(\omega) = \sqrt{U_t(\omega) I_t(\omega) \frac{\rho c}{2A_{ER} R_{RT} e^{-2\alpha d_1} G_{tt}}} . \quad (K.4)$$

A normal incidence reflection on the reflector is necessary for the self-calibration. This is ensured by maximizing the waveform reflection from the reflector as measured by the transducer. The driven electrical current I_t is measured with the auxiliary transducer in the output mode. The input voltage U_t is measured when the auxiliary transducer is in the input mode. It should be an open-circuit voltage, and electrical corrections should be applied to the measured current and voltage.

In sequence, the **hydrophone** active element is placed in a determined spot in the ultrasonic field, and the acoustic pressure is maximized in order to assure the alignment of the **hydrophone** active element symmetry axis and the transducer symmetry axis. The acoustic pressure at this point is calculated using the following expression:

$$p_h(\omega) = p_0(\omega) e^{-\alpha d_h} G_{th} \quad (K.5)$$

where p_h is the measured acoustic pressure incident on the **hydrophone's** active element if the **hydrophone** were removed, d_h is the distance from the transducer surface to the active hydrophone element measured on the symmetry axis, and G_{th} is the correction that accounts for the diffraction in the propagation field and is related to the generation transducer and the reception by the **hydrophone**.

The open-circuit voltage from the **hydrophone** U_h should be measured with p_h incident on its active element. The end of cable sensitivity is therefore given as

$$M(\omega) = \frac{U_h(\omega)}{p_h(\omega)} \quad (K.6)$$

K.3 Electrical quantities

The transmitting current, I_t , shall be measured as precisely as possible, which can be performed in many different ways. Measuring the voltage drop across a calibrated impedance or using a current probe are typical electrical setups.

The output voltage from the transducer in the receiving mode, U_t , shall be measured unloaded by the transducer, i.e. as an open circuit voltage. One way to perform that is to measure the current over a short circuit replacing the transducer. The open circuit voltage is

$$U_t(\omega) = U_{load}(\omega) \frac{I_{sc}(\omega)}{I_t(\omega)} \quad (K.7)$$

where U_{load} is the voltage measured with the transducer coupled to the system and I_{sc} is the current measured over a short circuit jumper replacing the transducer.

In the case of a constant load assumed throughout the calibration process, corrections described in Annex C could be applied directly to the final assessed sensitivity.

K.4 Diffraction correction and loss due to nonlinear sound propagation

Due to the finite size of auxiliary transducers and **hydrophones**, a diffraction pattern develops in the ultrasonic field. In the two-transducer reciprocity method, two diffraction corrections are applied: 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**, and G_{tt} , correction due the generation and the reception by the transducer. Many references can be used to theoretically describe the diffraction loss in ultrasonic fields [83, 86, 87], and a numerical implementation of diffraction corrections can be applied [88, 89, 90, 91].

K.5 Ultrasonic field

For the two-transducer reciprocity calibration, the ultrasonic field is shaped by the influence of many aspects, mainly:

- diffraction pattern for both the auxiliary transducer and hydrophone (see K.3);
- signal type (see Annex G and [8, 80]);
- reflector reflection coefficient (see 9.4.2);
- water path attenuation (see [92]);
- speed of sound (see [36]).

The amplitude attenuation coefficient for plane ultrasonic waves, α , in the megahertz frequency range is proportional to f^2 , and should be taken from a polynomial fit as a function of temperature T in the temperature range from 0 °C to 60 °C [92]:

$$\alpha / f^2 = \left(\begin{array}{l} 5,685 \cdot 10^1 - 3,025 \cdot 10^0 \{T\} \\ + 1,174 \cdot 10^{-1} \{T\}^2 - 2,954 \cdot 10^{-3} \times \{T\}^3 \\ + 3,970 \cdot 10^{-5} \{T\}^4 - 2,111 \cdot 10^{-7} \{T\}^5 \end{array} \right) \times 10^{-15} \text{Hz}^{-2} \cdot \text{m}^{-1} \quad (\text{K.8})$$

NOTE 1 $\{T\}$ denotes the numerical value of the temperature in °C.

NOTE 2 If the amplitude attenuation coefficient in m^{-1} is going to be given in dB m^{-1} , its numerical value should be multiplied by $20 \cdot \log_{10}(e) = 8,69$.

The speed of sound is presented in tables in [36], and polynomial fits are available for different accuracies, temperature ranges, and barometric pressures. The contribution for the uncertainty budget should be taken into account regarding the formula used to assess the speed of sound.

- a) Temperature range: 0 °C to 100 °C at atmospheric pressure; accuracy better than $0,02 \text{ ms}^{-1}$ (see [93])

$$c = \left(\begin{array}{l} 1402,39 + 5,03836 \{T\} - 0,0581173 \{T\}^2 \\ + 3,34638 \cdot 10^{-4} \{T\}^3 - 1,48260 \cdot 10^{-6} \{T\}^4 \\ + 3,16585 \cdot 10^{-9} \{T\}^5 \end{array} \right) \text{m} \cdot \text{s}^{-1} \quad (\text{K.9})$$

- b) Temperature range: 10 °C to 40 °C at atmospheric pressure; accuracy better than $0,18 \text{ ms}^{-1}$ (see [93])

$$c = (1405,03 + 4,624 \{T\} - 0,0383 \{T\}^2) \text{m} \cdot \text{s}^{-1} \quad (\text{K.10})$$

- c) Temperature range: 15 °C to 35 °C at atmospheric pressure; accuracy better than 0,20 ms⁻¹ (see [94])

$$c = (1404,3 + 4,7 \{T\} - 0,04 \{T\}^2) \text{ m} \cdot \text{s}^{-1} \quad (\text{K.11})$$

For the atmospheric pressure dependence of the speed of sound, see [95].

K.6 Experimental setup

K.6.1 General

Different experimental arrangements have been proposed to perform the two-transducer reciprocity calibration. Regardless of the electrical setup, the main concern in the experimental preparation comprises the positioning of the auxiliary transducer, reflector, and **hydrophone**. Three experimental setups are shown, each of them presenting advantages and drawbacks.

K.6.2 Twisting reflector

Figure K.1 depicts an arrangement in which the reflector is twisted between the two steps of the calibration procedure. Care should be taken to avoid a large angle of rotation of the reflector. A maximum of 10° would be acceptable, but the uncertainty of the **hydrophone** voltage measurement due to non-normal reflection should be considered. Moreover, for large membrane **hydrophones**, it could be a negative issue to set the rotation angle small. Another negative aspect of this arrangement is that it may not be simple to rotate large and heavy stainless steel reflectors with appropriate accuracy.

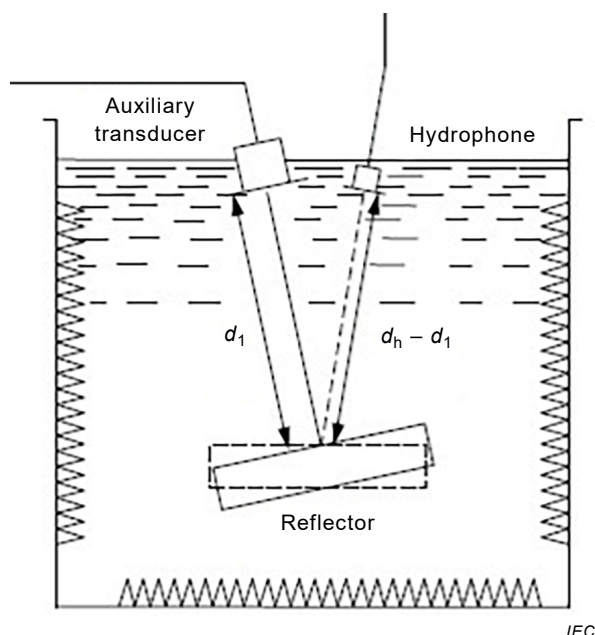


Figure K.1 – Experimental setup with a twisting reflector [83]

K.6.3 Translational reflector

Figure K.2 discloses an arrangement in which the reflector is inserted in the path between the auxiliary transducer and the **hydrophone**.

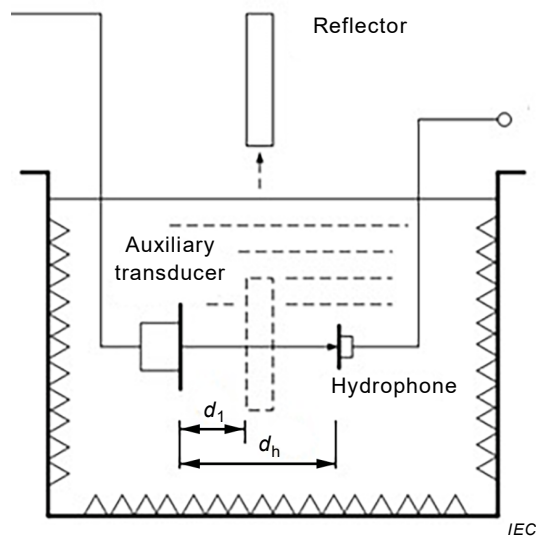


Figure K.2 – Experimental setup with a translational reflector [84]

K.6.4 Translational auxiliary transducer

In Figure K.3, the **hydrophone** and the reflector remain still during the measurement procedure, and the moving element is the transducer.

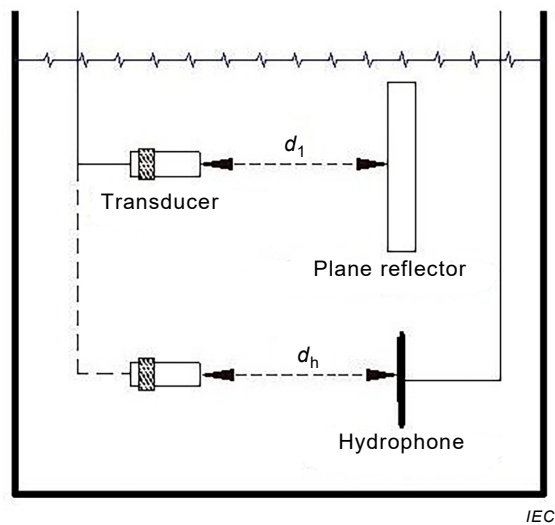


Figure K.3 – Experimental setup with a translational auxiliary transducer [85]

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Add the following references:

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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 require calibration. The purpose of this part of IEC 62127 is to specify those calibration methods to be used in determining the response of a **hydrophone** in the ultrasonic range, i.e. above 20 kHz up to a frequency of 40 MHz. The main **hydrophone** application in this context lies in the measurement of ultrasonic fields emitted by medical diagnostic equipment in water. **Hydrophone** behaviour over this wide frequency band is required 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 required 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. With regard to other pressure sensor types, such as those based on fibre optics, some of the requirements of this standard 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 have to be dealt with in a revised version of this standard or in a separate one.

NOTE This standard covers the ultrasonic frequency range, from 20 kHz to an upper frequency of 40 MHz. Standards dealing with **hydrophone** properties (IEC 62127-3) and **hydrophone** use (IEC 62127-1) are being developed in parallel as part of a programme of maintenance activities aimed at restructuring and merging, where possible, all existing ultrasonic **hydrophone** standards. This will eventually lead to unified standards covering the whole field of practical **hydrophone** application.

ULTRASONICS — HYDROPHONES —

Part 2: Calibration for ultrasonic fields up to 40 MHz

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 standard.

This standard is applicable to

- **hydrophones** used for measurements made in water and in the ultrasonic frequency range up to 40 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 [1].

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

NOTE 2 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. The clauses within this standard remain valid, although, in these cases, special attention should be paid 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 referenced documents are indispensable for the application 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, *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 61161, *Ultrasonics – Power measurement – Radiation force balances and performance requirements*

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

IEC 62127-1:2007, *Ultrasonics – Hydrophones – Part 1: Measurement and characterization of medical ultrasonic fields up to 40 MHz*

Amendment 1:2013 Ⓐ

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

3 Terms, definitions and symbols

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

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

3.2

beam axis

straight line that passes through the **beam centrepoin**ts 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**

NOTE 1 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 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 synchronisation with the scanframe is not available the term **pulse-pressure-squared integral** may be replaced by **temporal average intensity**.

NOTE 3 See Figure 1 of IEC 62127-1.

NOTE 4 Definition adopted from IEC 62127-1.

3.3

beam centrepoin

position determined by the intersection of two lines passing through the **beamwidth midpoin**ts of two orthogonal planes, xz and yz

NOTE Definition adopted from IEC 61828:2001.

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 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 synchronisation with the scanframe is not available the term **pulse-pressure-squared integral** may be replaced by **temporal average intensity**.

NOTE 2 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 **Beamwidth** is expressed in metres (m).

NOTE 4 Definition adopted from IEC 62127-1.

3.5

beamwidth midpoint

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

NOTE 1 The average is taken over 20 beamwidth levels corresponding to intervals in the -0,1 dB to -26 dB range (see IEC 61828, Clause B.2).

NOTE 2 Definition adopted from IEC 61828:2001.

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

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 The **diametrical beam scan** may extend to different distances on either side of the **beam axis**.

NOTE 2 Definition adopted from IEC 62127-1.

3.8

directional response

description, generally presented graphically, 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 Definition adopted from IEC 60565.

3.9

A_1 effective radius of a non-focusing ultrasonic transducer A_1

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 The A_1 effective radius of a non-focusing ultrasonic transducer A_1 is expressed in metres (m).

NOTE 2 Definition adopted from IEC 62127-1.

3.10

effective hydrophone radius

a_h , a_{h3} , a_{h6}

radius of a stiff disc 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 2 The **effective hydrophone radius** is expressed in metres (m).

NOTE 3 The radius is usually a function of frequency. For representative experimental data, see [2].

NOTE 4 Definition adopted from IEC 62127-3.

3.11
electric load impedance
 Z_L

complex electric input impedance (consisting of a real and an imaginary part) to which the **hydrophone assembly** output cable is connected or is to be connected

NOTE 1 The **electric load impedance** is expressed in ohms (Ω).

NOTE 2 Definition adopted from IEC 62127-3.

3.12
end-of-cable loaded sensitivity
end-of-cable loaded sensitivity of a hydrophone (or hydrophone-assembly)
 $M_L(f)$

ratio of the instantaneous voltage 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 acoustic pressure** in the undisturbed free field of a plane wave in the position of the reference centre of the **hydrophone** if the **hydrophone** were removed

NOTE 1 **End-of-cable loaded sensitivity** is expressed in volts per pascal (V/Pa).

NOTE 2 Definition adopted from IEC 62127-3.

3.13
end-of-cable open-circuit sensitivity
end-of-cable open-circuit sensitivity of a hydrophone
 $M_c(f)$

ratio of the instantaneous open-circuit voltage at the end of any integral cable or output connector of a **hydrophone** to the **instantaneous acoustic pressure** in the undisturbed free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

NOTE 1 **End-of-cable open-circuit sensitivity** is expressed in volts per pascal (V/Pa).

NOTE 2 Definition adopted from IEC 62127-3.

3.14
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 This surface is either directly in contact with the patient or is in contact with a water or liquid path to the patient (see [A1](#)) Figure 1 [A1](#) of IEC 62127-1).

NOTE 2 Definition adopted from IEC 61828:2001.

3.15
far field

[A1](#) region of the field where $z > z_T$ aligned along the **beam axis** for planar non-focusing transducers. [A1](#)

NOTE 1 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 The term "**far field**" is used in this standard 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).

[A1](#) NOTE 3 If the shape of the transducer aperture produces several **transition distances**, the one furthest from the transducer shall be used.

[SOURCE: IEC 62127-1:2007/Amendment 1:2013, definition 3.28] [A1](#)

3.16

free field

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

NOTE Definition adopted from IEC 60565: 2006, 3.13.

3.17

hydrophone

transducer that produces electric signals in response to waterborne acoustic signals.

NOTE Definition adopted from IEC 60050-801, 801-32-26.

3.18

hydrophone assembly

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

NOTE 2 Definition adopted from IEC 62127-3.

3.19

hydrophone axis

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

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

NOTE 2 Definition adopted from IEC 62127-3.

3.20

hydrophone geometrical radius

geometrical radius of a hydrophone active element

a_g

radius defined by the dimensions of the active element of a **hydrophone**

NOTE 1 The **hydrophone geometrical radius** is expressed in metres (m)

NOTE 2 Definition adopted from IEC 62127-3.

3.21

hydrophone pre-amplifier

active electronic device connected to, or to be connected to, a particular hydrophone and reducing its output impedance

NOTE 1 A **hydrophone pre-amplifier** requires a supply voltage (or supply voltages).

NOTE 2 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.

NOTE 3 Definition adopted from IEC 62127-3.

3.22

instantaneous acoustic pressure

$p(t)$

pressure minus the ambient pressure at a particular instant in time and at a particular point in an acoustic field (see also IEC 60050-801, 801-21-19)

NOTE 1 **Instantaneous acoustic pressure** is expressed in pascal (Pa).

NOTE 2 Definition adopted from IEC 62127-1.

3.23

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 **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 International Standard 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**. A_1

NOTE 2 A_1 **Instantaneous intensity** A_1 is expressed in watts per square metre (W/m^2).

3.24

reference centre

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

NOTE Unless stated otherwise (explicitly and quantitatively) by the manufacturer, it is understood for the purposes of this standard that this is given by the geometrical centre of the front surface of the **hydrophone** active element.

(See IEC 60565: 2006, 3.25)

3.25

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 See the ISO Guide to the Expression of Uncertainty in Measurement [3], 2.2.3.

A_1 3.26

derived instantaneous intensity

approximation of the **instantaneous intensity**

For the measurement purposes referred to in this International Standard, and under conditions of sufficient distance from the transducer (at least one transducer diameter, or an equivalent transducer dimension in the case of a non-circular transducer) the **derived instantaneous intensity** is determined by

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

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 For measurement purposes referred to in this International Standard, the **derived instantaneous intensity** is an approximation of the **instantaneous intensity**.

NOTE 2 Increased uncertainty should be taken into account for measurements very close to the transducer.

NOTE 3 **Derived instantaneous intensity** is expressed in watts per square metre (W/m^2).

[SOURCE: IEC 62127-1:2007/ Amendment 1:2013, definition 3.78] A_1

A1 3.27

effective wavelength

λ

longitudinal speed of sound in the propagation medium divided by the **arithmetic-mean working frequency**

NOTE **Effective wavelength** is expressed in metres (m).

[SOURCE:IEC 61828:2001, definition 4.2.24].

3.28

longitudinal plane

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

NOTE See Figure 1 in IEC 62127-1.

[SOURCE: IEC 62127-1:2007, definition 3.35].

3.29

source aperture plane

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

[SOURCE:IEC 61828:2001, definition 4.2.67].

3.30

source aperture width

L_{SA}

in a specified **longitudinal plane**, the greatest –20 dB **beamwidth** along the line of intersection between the designated **longitudinal plane** and the **source aperture plane**

NOTE 1 See Figure 2 in IEC 61828 2001.

NOTE 2 **Source aperture width** is expressed in metres (m).

[SOURCE:IEC 61828, definition 4.2.68].

3.31

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 See Figure 4 in IEC 62127-1 .

NOTE 2 **Transducer aperture width** is expressed in metres (m).

[SOURCE:IEC 62127-1:2007/ Amendment 1:2013, definition 3.87].

3.32

transition distance

z_T

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

- from design: the **transition distance** is the equivalent area of the ultrasonic **transducer aperture width** divided by π times the **effective wavelength**, λ ;
- for measurements, the **transition distance** is the equivalent area of the **source aperture width** divided by π times the **effective wavelength**. **A1**

[A1] 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 61828:2001, definition 4.2.75, modified: There is significant difference in the layout of the definition] **[A1]**

4 List of symbols

a_h	effective hydrophone radius (a_{h3} , a_{h6} : with special reference to a 3 dB or 6 dB definition, respectively)
a_g	hydrophone geometrical radius
a_{max}	maximum effective radius for a specific hydrophone application
a_P	lateral distance from the beam axis (a_{PmaxE} , a_{PmaxH} : maximum values with respect to avoiding edge wave and head wave interference, respectively)
a_t	[A1] effective radius of an non-focusing ultrasonic transducer [A1]
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
$D(\theta)$	normalized directional response function
e	base of natural logarithms
f	frequency
f_i	fundamental drive frequency of a signal used to generate nonlinear distortion
f_u	upper frequency limit of the stated frequency band of a hydrophone
I_p	magnitude of the instantaneous intensity assuming proportionality with acoustic pressure squared
$\vec{I}(x,y,z,t)$	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
F	geometric focal length of a focusing transducer
j_{max}	the number of the farthest scan point in a radial scan
k	circular wave number ($= 2\pi/\lambda$)
[A1] L_{TA}	transducer aperture width
L_{SA}	source aperture width [A1]
$\underline{M}$	general symbol for the complex hydrophone sensitivity, $M = \underline{M} $ being its modulus and $\arg(\underline{M})$ being its argument ($=$ phase angle)
$M_c(f)$	end-of-cable open-circuit sensitivity
$M_L(f)$	end-of-cable loaded sensitivity

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
$p(x,y,z,t)$	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_{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
t_H	arrival time of the nearest head wave
t_{TDS}	time available for a free field measurement in time delay spectrometry
TF	acoustic transmission factor
$U_L(x,y,z,t)$	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 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 according to 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
Δz	distance difference
$\underline{Z}_h$	complex electric output impedance of a hydrophone
$\underline{Z}_L$	complex electric load impedance
$\boxed{A_1} z_T$	transition distance $\boxed{A_1}$
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 (θ_3 , θ_6 : with special reference to 3 dB and 6 dB defined levels)
λ	ultrasonic wavelength
λ_1	optical wavelength
ξ	$\pi/2$ times the Rayleigh length (a_t^2/λ , see IEC 61828) of a focusing transducer
ρ	(mass) density of the measurement liquid (water)
ρc	specific acoustic impedance
σ	nonlinear distortion parameter
σ_m	nonlinear propagation 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**, $u(t)$, may be presented in the form:

$$u(t) = p(t) * m(t) \quad (2)$$

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

In agreement with present measurement practice, **hydrophones** are dealt with in this standard as amplitude (magnitude) sensors and not as phase sensors. However, there is some evidence that phase measurement will become more important in the future, particularly due to the application of deconvolution methods (see IEC 62127-1), which require the complex hydrophone transfer function. If indeed phase measurements become important, this standard will need revision, with more rigorous requirements being necessary for that kind of measurement. A summary of current capability for (relative) phase measurement is provided in Annex I.

NOTE 1 Accordingly, the **hydrophone** sensitivity is understood as a real quantity (expressing the ratio of amplitudes) throughout this standard.

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 2 “Absolute” **hydrophone** calibration is understood here in the sense of “without reference to another **hydrophone**”. This is sometimes also referred to as “primary” or “substitution” procedure, which means a sensitivity comparison with a calibrated reference **hydrophone**. The reference **hydrophone** itself may 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**. Clauses 9, 10, 11, Annexes D, F and H deal with the former procedure. The latter procedure is dealt with in detail in Clause 12. It should be noted that a substitution calibration usually involves both steps and that the interested user should refer to both Clause 12 and 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 40 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.

