

CONSOLIDATED VERSION

VERSION CONSOLIDÉE



**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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ULTRASONICS – HYDROPHONES –

Part 2: Calibration for ultrasonic fields up to 40 MHz

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In this Redline version, a vertical line in the margin shows where the technical content is modified by amendments 1 and 2. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC 62127-2 has been prepared by IEC technical committee 87: Ultrasonics.

IEC 62127-1, IEC 62127-2 and IEC 62127-3 are being published simultaneously.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

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

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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 ~~non-linear~~ 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:~~1994~~, *International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics*

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

IEC 61161:~~2006~~, *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 61828:~~2006~~, *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 centrepoints** of two planes perpendicular to the line which connects the point of maximal **pulse-pressure-squared integral** with the centre of the **external transducer aperture**

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 centrepoint

position determined by the intersection of two lines passing through the **beamwidth midpoints** 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

effective radius of a ~~non-focused~~ 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 The **effective radius of a ~~non-focused~~ non-focusing ultrasonic transducer** 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 Figure 2.1 of IEC 62127-1).

NOTE 2 Definition adopted from IEC 61828:2001.

3.15 far field

~~acoustic (sound) field at distances from an **ultrasonic transducer** where the values of the **instantaneous acoustic pressure** and particle velocity are substantially in phase (see also IEC 60050-801, 801-23-30)~~

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

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).

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]

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 if it is reasonable to assume far field conditions,~~ 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**, ~~it is~~ can be approximated ~~as~~ by the **derived instantaneous intensity**.

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

where

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

ρ is the **density of the medium**;

c is the **velocity of sound in the medium**.

NOTE 2 **Instantaneous intensity** is expressed in watts per **square metre** ~~squared~~ (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.

3.26

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 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/m²).

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

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**.

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]

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	effective radius of a ~~non-focused~~ non-focusing ultrasonic transducer
A_g	geometrical area of an ultrasonic transducer
B/A	Fox-Wallace ~~non-linearity~~ 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 ~~non-linear~~ 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
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
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
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
$\underline{M}$	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
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_0	total ultrasonic power emitted by a transducer
rf	radio-frequency signals
r	distance from the ultrasonic beam centre to a scan point
R	$(l/\pi a_1^2)$ - 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
TF	acoustic transmission factor
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 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
Z_{RT}	characteristic acoustic impedance of the reflector
z_T	transition distance
Δz	distance difference
$\underline{Z}_h$	complex electric output impedance of a hydrophone
$\underline{Z}_L$	complex electric load impedance
α	amplitude attenuation coefficient of plane waves in a medium (usually water)
β	~~non-linearity~~ 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~~ characteristic acoustic impedance of the measurement liquid (water)
σ	~~non-linear~~ nonlinear distortion parameter
σ_m	~~non-linear~~ 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” 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 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, and 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 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 |
| <ul style="list-style-type: none">– Calibration without a standard transducer in a free field, between 50 kHz and 15 MHz. | |
| b) Free field calibration by planar scanning | Clause 10 |
| <ul style="list-style-type: none">– Calibration with a standard transducer in a free field, between 500 kHz and 15 MHz. | |
| c) Free field calibration by optical interferometry | Clause 11 |
| <ul style="list-style-type: none">– 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 |
| <ul style="list-style-type: none">– Calibration by comparison with a calibrated standard hydrophone, between 50 kHz and 40 MHz. | |

Table 1 – List of typical uncertainty values obtained by the calibration methods specified in this standard and for the frequency range listed here

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 %
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 may be carried out using optical interferometry. This lower limit is typically controlled by reflections from the water tanks or from the device being calibrated.			

5.3 Reporting of results

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.

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 standard, sensitivity and **uncertainty** values may be given separately for several frequency intervals. The frequency response may 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 might 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 Care should be taken in designing the **hydrophone** mount at low frequencies (below 200 kHz) where the acoustic wavelengths are sufficiently large that the use of long-bursts may lead to the direct acoustic signal being contaminated by reflections from the mount. The importance of the effect may be investigated through varying the burst length and observing the influence of reflections on the **hydrophone** signal. Acoustic absorbers may be useful in suppressing these reflections. **Hydrophone** sensitivity may also be affected by the way the **hydrophone** is clamped, and again this may be evaluated by systematically investigating the various configurations.

- 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 ~~5~~ 6 The last point is important, as it has been found in the literature [4] 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 ~~6~~ 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 might need to increase their 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 may 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 may 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 may 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 may 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 standard, 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 equation $\sin[\xi(1/z - 1/F)]/[\xi(1/z - 1/F)] = 0,89$, where $\xi = \pi a_t^2 f / (2c)$, 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 ~~dependence~~ **variation** of the **hydrophone** output voltage should be checked when the lateral **hydrophone** position is ~~varied~~ **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 $r = 0,107 c z / (f a_t)$ for a 0,5 dB amplitude reduction and $r = 0,151 c z / (f a_t)$ 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 to that under which it will be used. If this is not possible, the

corrections to **hydrophone** sensitivity and frequency response values may 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.

NOTE 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). 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 small-amplitude 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 radius of the hydrophone** 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 [5, 6, 7].

NOTE 1 If the **hydrophone** is carefully designed to have a known or well-defined active surface, it might be 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 may 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, ~~and also to allow the distance between the transducer, the hydrophone or any reflector (for the reciprocity method specified in Clause 9) to be set at a value equal to at least 1,5 times the near field distance of any of the transducers used.~~ 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 could 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, care needs to be exercised 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 analyzer, spectrum analyzer or other appropriate instrument with sufficient bandwidth and sensitivity. Additional amplification of the signal from the **hydrophone** or **hydrophone pre-amplifier** may 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 analyzer, spectrum analyzer, 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 analyzer: for recording temporal waveforms, the sampling rate shall be at least $20f$ megasamples/second, where f is in MHz. Also, the gain shall be adjusted to allow at least seven significant bits in the digitized waveform.

NOTE For the 40 MHz upper frequency limit specified in this standard, this will require a sampling rate of at least 800 MHz.

7 Electrical considerations

7.1 Signal type

The signal used for the calibration may be either sinusoidal (continuous wave), swept sinusoidal [8] 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 may 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 may 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 may 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 may 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 Attention should be paid to the appropriateness of the output impedance of the hydrophone/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 may 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 may 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 may be made without significant loss of accuracy. It is preferable that the signal amplitude 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 might 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 may 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 the following subclauses.

8.2 Wetting

~~To make sure that the **hydrophone** is wetted properly by the water without trapping an air film or bubbles on its surface, a wetting agent may be applied to the whole transducer surface. No dry patches should be visible on the **hydrophone** when it is immersed and then removed from the water.~~ 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.

In situations where the mount does have an effect, the **hydrophone** should be calibrated in the same mount that will be used for measurements made with the **hydrophone** in the field. If the mount influences the measured sensitivity, then the calibration is only valid for the type of mount used. Where the **hydrophone** is sensitive to the type of support/mount, a description of the mounting arrangement should be stated with the results.

8.4 Influence of cable

If the cable to the **hydrophone** needs to be lengthened for the purposes of the calibration, the electrical impedance of the extension cable shall be measured separately in order to calculate the influence of electrical loading. A description of how to account for the influence of electrical loading is given in Annex C.

9 Free field reciprocity calibration

9.1 General

This clause specifies the primary **reference measurement procedure** (see JCGM 200:2012, 2.8 [79]) calibration of **hydrophones** ~~in a virtually unlimited volume of water, i.e.~~ under **free field** conditions using the principle of reciprocity.

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].

9.2 Object

The object of this clause is to specify various methods of absolute calibration of laboratory standard **hydrophones** with the smallest obtainable **uncertainty**. These methods cover the frequency range between 50 kHz and 15 MHz.

9.3 General principles

9.3.1 General

For a linear, passive, reversible electroacoustic transducer, a well-defined relationship exists between its free field sensitivity as a detector and its transmitting response to current. This relationship is expressed for a particular arrangement of the components within a system of transducers in the definition of the reciprocity coefficient.

All calibrations based on the principle of reciprocity require the use of a reciprocal transducer as both a transmitter and a receiver. Provided changes occurring within the acoustic field between transmission and reception are known, then the transmitting response and the receiving sensitivity of the transducer can be determined directly by measuring the drive current and received signal voltage. One obvious advantage of this method is that the required acoustic parameters are determined by the measurement of electrical quantities only. In practice, calibrations based on the principle of reciprocity can take several forms, briefly specified below.

9.3.2 Three-transducer reciprocity calibration method

A procedure commonly used for applications in marine acoustics involves the use of three transducers (see IEC 60565:2006).

This method can be difficult to implement at higher frequencies, however, because of the need for greater accuracy in the adjustment of transducer position and orientation, and because of the complex nature of the directional response characteristics of transducers used at frequencies of a few MHz. Consequently, this method is recommended for calibrations in the frequency range 50 kHz to 1 MHz.

9.3.3 Self-reciprocity calibration method

Calibration by self-reciprocity, which involves the use of only the test transducer and a reflector, requires a minimum of geometrical adjustment to be carried out. This technique is not, however, generally applicable to high-frequency **hydrophones** which, because of their size, have insufficient acoustic output for an adequate signal-to-noise ratio in the received signal (the minimum diameter for a practical transducer is about 2 mm).

9.3.4 Two-transducer reciprocity calibration method

For the frequency range 1 MHz to 15 MHz, standard **hydrophones** can be calibrated by the two-transducer method in which the **hydrophone** is placed within the known field generated by an auxiliary transducer; a field which has previously been quantified by self-reciprocity

procedures. The technique is capable of providing calibration data of an accuracy consistent with performance specifications laid down for the standard **hydrophone**, but does not involve such critical adjustment of component positions and orientations as the three-transducer method.

9.4 Two-transducer reciprocity calibration method

NOTE Within this standard, information on this calibration technique is also presented in Annex K and is provided for information purposes.

9.4.1 Apparatus Auxiliary transducers

~~The reflector should comprise a stainless steel disc of sufficient diameter to encompass the entire ultrasonic beam from any of the auxiliary transducers at a distance from its surface of at least 1,5 times the near field distance, given by $N_1 = a_t^2/\lambda$ where a_t is the effective radius of the ultrasonic transducer, and λ the ultrasonic wavelength in water at its frequency of operation.~~

~~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 the lowest frequency tone burst to be used. The reflector shall also be flat to $\pm 10\ \mu\text{m}$, with a surface finish good to $\pm 5\ \mu\text{m}$.~~

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 Reflector

~~Rotate the reflector through an angle of approximately 10° about an axis parallel to its surface and perpendicular to the line joining the acoustic centres of the **hydrophones** and auxiliary transducer.~~

~~NOTE This method has been improved through a coaxial configuration of the **hydrophone** and the auxiliary transducer with the reflector in the middle of them. In the configuration, the auxiliary transducer is calibrated and then the reflector is removed to calibrate the **hydrophone**. This can avoid the error caused by rotation of the reflector and make the alignment of the **hydrophone** and auxiliary reflector easier, and the error can be reduced to about 0,5 dB.~~

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: $R_v < 5\ \mu\text{m}$; $R_a < 1\ \mu\text{m}$). 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.

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 analytical or 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.

10 Free field calibration by planar scanning

10.1 General

This clause specifies the calibration of **hydrophones** using the planar scanning method.

10.2 Object

The object of this clause is to specify the planar scanning method of calibrating a **hydrophone**. This utilizes a reference transducer whose output power is known. This transducer or source can be a standard device of known and reproducible output power, characterized traceable to national standards, or it may be calibrated prior to the planar scanning calibration, using, for example a radiation force balance in accordance with IEC 61161. The method covers the frequency range between 500 kHz and 15 MHz, although it can be applied at higher frequencies, with degraded uncertainties.

10.3 General principle

If M_L is the **end-of-cable loaded sensitivity of a hydrophone** whose **reference centre** is at coordinate position (x,y,z) , the **instantaneous acoustic pressure** $p(x,y,z,t)$ is related to the measured end-of-cable voltage $U_L(x,y,z,t)$ by

$$p(x,y,z,t) = U_L(x,y,z,t)/M_L \quad (3)$$

where

(x,y,z) are the coordinates of any point in the field; and

t is any instant in time.

Here, $p(x,y,z,t)$ relates to the acoustic pressure in a plane wave at the **hydrophone reference centre** if the **hydrophone** were removed.

The **instantaneous intensity** vector, $\vec{I}(x,y,z,t)$, at a reference point in an ultrasonic field from a transducer whose centre is at the origin of the coordinate system is given by

$$\vec{I}(x,y,z,t) = p(x,y,z,t) \cdot \vec{v}(x,y,z,t) \quad (4)$$

where

$\vec{v}(x,y,z,t)$ is the instantaneous particle velocity vector at the reference point.

The components of $\vec{I}$ and $\vec{v}$ in the propagation direction will be considered, thereby restricting them to the scalar quantities I and v .

For progressive wave propagation under certain conditions ($a_t/l \leq 0,5$), where l is the axial distance from the transducer, the **instantaneous intensity** can be given [9] by

$$I(x,y,z,t) = [p(x,y,z,t)]^2 / (\rho c) \quad (5)$$

where

ρ is the (mass) density of the measurement liquid (water); and

c is the speed of sound in water.

(See Annex E for the temperature dependence of ρ and c for water, the recommended transmission medium used for power measurements.)

The total ultrasonic power $P(l)$ transmitted through a plane at $z = l$ perpendicular to the z -axis is given by

$$P(l) = \iint \overline{I(x,y,l,t)} \cos \theta \, dy \, dx \quad (6)$$

where

$dy \, dx$ is an elemental area in the plane $z = l$;

θ is the angle between the z -axis and the propagation direction, the integral denotes integration over the entire plane.

NOTE 1 At the distances l considered in this standard (greater than a_t^2/λ where a_t is the effective radius of the ultrasonic transducer), θ can be considered to be the angle between the z -axis and the line joining the centre of the transducer to the centre of the **hydrophone**.

The bar in equation (6) indicates the time-averaged value defined for any quantity g by

$$\bar{g} = \lim(T \rightarrow \infty) \left[\left(\frac{1}{2T} \right) \int_{-T}^T g(t) dt \right] \quad (7)$$

Taking the time-average of equation (5)

$$\overline{l(x,y,z,t)} = \overline{p(x,y,z,t)^2 / (\rho c)} \quad (8)$$

and from equation (3)

$$\overline{l(x,y,z,t)} = \overline{U_L(x,y,z,t)^2 / (M_L^2 \rho c)} \quad (9)$$

where

$U_L(x,y,z,t)$ the end-of-cable voltage for a **hydrophone** with the hydrophone at reference point (x,y,z) and at time t .

Here, it is assumed that the time-averaged value of the square of the end-of-cable voltage is derived. From equation (5), on the plane $z = l$ and neglecting the $\cos(\theta)$ term (see D.3.9), the **end-of-cable loaded sensitivity**, M_L , is given by

$$M_L = \left\{ \frac{1}{P(l) \rho c} \iint \left[\overline{U_L(x,y,l,t)^2} \right] dy dx \right\}^{1/2} \quad (10)$$

The **end-of-cable loaded sensitivity of a hydrophone** can, therefore, be determined by scanning the hydrophone over a plane in the ultrasonic beam, and dividing the integral of the average value of the square of the **hydrophone** signal by the total power in the beam.

NOTE 2 The **end-of-cable open-circuit sensitivity**, M_c , may be determined through a knowledge of the electrical impedances of the **hydrophone** and amplifier determined in the way described in Annex C.

10.4 Procedural requirements

10.4.1 Hydrophone scanning

There are several ways of scanning the **hydrophone** over the plane $z = l$ in the ultrasonic beam. The most comprehensive is to obtain a rectangular array of sample points by moving the **hydrophone** in a two-dimensional raster scan. An alternative scanning procedure is possible if the beam profile from the transducer can be assumed to be approximately cylindrically symmetrical. In this case, a number of **diametrical beam scans** may be performed. These scans should pass through the ultrasonic **beam centre** and be spaced at equal angular increments. For example, if two scans are performed, they should be at 90° to each other. Guidance on the choice of scan types can be found in Annex D.

10.5 Procedure

10.5.1 Power measurement

Use a transducer with a plane disc active element of known total output power at a particular frequency f . The transducer may be a standard transducer [10], in which case the output power shall be known in terms of the particular drive voltage.

Alternatively, determine the output power using the radiation force method as specified in IEC 61161 [11].

Whichever method is used, determine the total ultrasonic power emitted by a transducer, P_0 , at the frequency f under continuous sinusoidal electrical excitation either at a particular drive voltage U_T or over a range of different applied voltages. These measurements provide a value for the output power divided by the square of the voltage (see IEC 61161).

10.5.2 Transducer mounting

Mount the transducer in a beam scanning tank and align it so that the transducer **beam axis** is parallel to the z-axis of the scanning system. Mount the **hydrophone** to be calibrated in the scanning tank and align it following the procedure specified in IEC 62127-1. At the end of this alignment procedure, the z-axis of the scanning system shall be parallel to both the **beam axis** of the transducer and to the direction of maximum sensitivity of the **hydrophone**.

NOTE Typical mounting arrangements commonly utilize the transducer and **hydrophone** mounted in either horizontal or vertical configurations. Whatever arrangement is used, relative alignment of the transducer and **hydrophone** and one of the axes of the scanning system (referred to above as the z-axis) should be maintained.

10.5.3 Measurement conditions

Drive the transducer using a gated sinusoidal excitation (tone-burst) containing a sufficient number of oscillations to ensure steady-state conditions of frequency f either at the particular drive voltage U_T or at a voltage within the range used in the radiation force technique. Position the **hydrophone** at $z = l$ in the far field of the transducer and locate the point of peak acoustic pressure. Choose the distance l carefully, taking account of spatial averaging, directivity and attenuation corrections (see Annex D) and the need for maximum signal-to-noise ratio.

NOTE A value of l in the range from a_t^2/λ to $3a_t^2/\lambda$ is generally satisfactory, where a_t is the **effective radius of a non-focused non-focusing ultrasonic transducer** and λ is the ultrasonic wavelength. The geometrical radius of the transducer may be used instead if the **effective radius of a non-focused non-focusing ultrasonic transducer** (a_t) is not known.

Use continuous wave excitation of the ultrasonic transducer if gating of the excitation is impractical. In this case, take extreme care to avoid reflections from the tank walls and the **hydrophone** and its support, and the formation of standing waves.

10.5.4 Measurements

Measure the amplitude of the output voltage of the **hydrophone** as the **hydrophone** is scanned over the plane $z = l$ perpendicular to the z-axis, either in a raster scan or in a number of **diametrical beam scans**. Measure the end-of-cable voltage $U_L(x, y, l, t)$ at the **hydrophone** as a function of the position of the **hydrophone** in the ultrasonic beam. Determine the extent of the scanned region from considerations of the noise level. Sum the square of the voltage over the area of the ultrasonic beam and derive a value for the **end-of-cable loaded sensitivity** of the **hydrophone** at the frequency f (see Annex D).

10.6 Corrections and sources of uncertainty

Make a final statement of the total **uncertainty** in the determination of the **end-of-cable loaded sensitivity of the hydrophone**. Detailed guidance on assessing these sources of uncertainty can be found in Annex D.

11 Free field calibration by optical interferometry

11.1 General

Currently, the free field calibration of **hydrophones** using optical techniques is restricted to specialized laboratories. Within this standard, information on this calibration technique is presented in Annex F and is provided for information purposes.

11.2 Principle

Typically, such techniques involve applying optics to determine the acoustic displacement produced by a transducer at a position in the acoustic field. These techniques are carried out using a thin membrane or foil positioned within the field, which moves in sympathy with the acoustic displacement. A surface of the foil, which is typically a few microns thick, is metallized to be optically reflecting. Using optical interferometric techniques, the displacement can be determined. In the far field of the transducer, the displacement is simply related to the acoustic pressure, allowing the latter to be determined at a point in the field. A **hydrophone** is calibrated by positioning it at the same location and determining the output voltage. Two realizations of the technique implemented by national standards laboratories can be found in Annex F.

12 Calibration by comparison using a standard hydrophone

12.1 General

In this clause two types of measurement are specified:

- Type I the determination of the **directional response**;
- Type II the comparison of sensitivity of two or more **hydrophones**.

12.2 Object

Both of the above measurements are referred to as "relative" measurements, which means that two or more measurements of the **hydrophone** output voltage under almost identical conditions are performed, with only one relevant parameter being varied, and that ratios of results (or logarithms of ratios of results) are considered.

NOTE As far as Type II is concerned, it is assumed in the following that the sensitivities of two **hydrophones** are being compared. This can easily be extended to three or more **hydrophones**.

12.3 Principle

In type I, the parameter changed is the **hydrophone** orientation angle. The **hydrophone** output voltage at a certain angle is considered in relation to the **hydrophone** output voltage in a reference orientation. In practice, of course, this will be done for a series of angles of rotation. This type of measurement is to obtain the **directional response** and the **effective radius** in accordance with IEC 62127-3.

In type II, the **hydrophone** itself is replaced by another one. It is understood here that one **hydrophone** is a reference **hydrophone** and the other is the **hydrophone** under test. This type of measurement is to obtain the sensitivity of the **hydrophone** under test, if the sensitivity of the reference **hydrophone** is known (from any calibration), and/or the frequency response of the **hydrophone** under test, if the frequency response of the reference **hydrophone** is known (from any calibration).

These relative measurements have the following features in common: they are performed in a water tank and in the ultrasonic field emitted by a transducer to be characterized below. It is vital that measurements carried out in relation to one another are performed as far as possible under identical conditions, meaning at the same position in the field, under the same excitation conditions (waveform and amplitude) and under the same environmental conditions (e.g. temperature), etc. The overall aim is to work under plane wave conditions.

For measurements of Type II, the uncertainty in the calibration is affected by the influence of spatial averaging. Methods of assessing this for various comparison configurations are specified in 12.6.

12.4 Procedural requirements

12.4.1 Source transducer

The ultrasonic source transducer for the measurements specified here shall be a circularly symmetric ultrasonic transducer for use in water. Various concepts exist related to the electrical excitation applied to the transducer, the transducer type and the nature of the acoustical waveform at the position of the hydrophone (linear, ~~non-linearly~~ nonlinearly distorted). These are described in Annex G. Either plane non-focusing transducers for hydrophone position concepts A, B or C or a focusing transducer for hydrophone position concepts D or E may be used. Depending on the waveform concept chosen, it shall be able to produce the necessary amplitude (adequate signal-to-noise in the **hydrophone** signal) at the frequency values of interest. This requirement includes the amplifier driving the transducer. The transducer shall be temporally stable and it shall not lead to a warm-up of the water bath exceeding the acceptable temperature drift limits.

NOTE The following check is recommended at the beginning of each measurement: in all cases where bursts or pulses are applied (temporal waveform concepts a, b, c), the **hydrophone** output signal should be observed when the transducer/**hydrophone** distance is varied over several millimeters, in order to ensure the absence of multiple transducer/ **hydrophone** echos from the signal received. If such echoes interfere with the signal received, a remedy can be to change the pulse repetition frequency.

12.4.2 Source transducer drive signal

The amplitude of the drive signal for the source transducer shall be stable to within ± 1 %; its centre frequency shall be stable to within $\pm 0,1$ %.

12.4.3 Measurement system

The measurement system shall conform to the requirements specified in Clause 6, Clause 7 and Clause 8.

12.5 Procedure

12.5.1 Measurements (Type I): determination of the directional response of a hydrophone

Position the **hydrophone** in the water tank in the field of the source transducer, according to the hydrophone position concept chosen (see Annex G) and with the **hydrophone reference centre** positioned on the transducer **beam axis**. Provide the measurement set-up with a mechanical device enabling the **hydrophone** to be rotated about an axis perpendicular to the **beam axis**, and achieve this independently for two rotation axes perpendicular to each other. The angle of rotation shall be measurable with an angle resolution equal to or better than $\theta_6/10$, where θ_6 is the -6 dB angle, which is known after the measurement or can be roughly inferred prior to the measurement using the **hydrophone geometrical radius**.

The **hydrophone** shall be rotated such that its **reference centre** is kept at the same place in the ultrasound field, in conformity to the positional accuracy requirements of Clause 6.

NOTE 1 For **hydrophones** of the unbacked membrane type, it is possible to check whether the **hydrophone** is actually rotating through its centre by rotating it through 180° and observing any resultant shift in the arrival time of the ultrasonic wave. For needle-type hydrophones, a special jig may need to be arranged, which ensures that the rotation is about the **reference centre**.

The measurement can be conducted in two ways. Either measure the **hydrophone** output voltage as a function of the rotation angle at a constant frequency; or measure the **hydrophone** output voltage as a function of frequency at a constant angle of rotation, and this for several values of the angle of rotation. In the latter case, rearrange the data obtained to yield again the **hydrophone** output voltage as a function of the angle of rotation at a constant frequency. Divide the **hydrophone** output voltage measured by that obtained in the orientation of maximum output voltage.

NOTE 2 To give an indication of the angular resolution required, the following assessment can be made. Assuming a **hydrophone** radius of 0,25 mm and $c = 1\,488$ m/s for water at 22 °C, the following values are obtained from equation (2) in IEC 62127-3: $\theta_6 = 8^\circ$ for a frequency of 15 MHz and $\theta_6 = 3^\circ$ for a frequency of 40 MHz.

NOTE 3 Values for the speed of sound c in water are listed in Annex E.

Use the directional response measurements to define the **effective radius** of the **hydrophone** active element using the two expressions:

$$a_{h3} = 1,62 \, c / (2\pi f \sin \theta_3) \quad (11)$$

and

$$a_{h6} = 2,22 \, c / (2\pi f \sin \theta_6) \quad (12)$$

where

θ_3 and θ_6 are the angles at which the hydrophone signal has decreased by –3 dB and –6 dB respectively.

NOTE 4 The **effective hydrophone radius** is important for the assessment of spatial averaging effects (see Annex J and IEC 62127-1). The **effective hydrophone radius** might be frequency- dependent for some types of **hydrophone** and for any particular **hydrophone** might be dependent on the chosen axis-of-rotation. Further information on the **effective hydrophone radius** may be found in IEC 62127-3.

12.5.2 Measurements (Type II): calibration by comparison using a standard hydrophone

This involves a series of measurements, where the **hydrophones** are placed alternately in the ultrasonic field. The minimum shall be a series of two measurements, one with each **hydrophone**. However, it is recommended that at least the first **hydrophone** be remeasured after the second one (this leading to a total of three measurements), to verify the stability of the applied acoustic field. A series of five or more single measurements would be even better.

In each single measurement, position the **hydrophone** in question in the water tank in the field of the source transducer and at the relevant place according to the hydrophone position concept chosen (see Annex G). Maximize the output signal by lateral and rotational adjustment of the **hydrophone**.

The **reference centre** of the **hydrophone** in question shall be positioned in the ultrasonic field exactly at the relevant place chosen for this measurement series, in conformity to the positional accuracy requirements of Clause 6. Provide the measurement set-up with the mechanical means to make this positioning possible. As an additional, useful procedure, observe the time-of-flight (propagation time) of the ultrasonic burst or pulse as an indicator of the transducer/**hydrophone** distance.

Measure the **hydrophone** output voltage as a function of frequency and consider this in relation to the result obtained with the other **hydrophone**.

If the measurements on the two **hydrophones** are not carried out under the same electrical loading conditions, clearly state this and give the prescriptions for calculating the **hydrophone** sensitivity ratio for the same loading conditions.

12.6 Maximum hydrophone size

In order to avoid measurement errors due to spatial averaging in the measurements specified in 12.5, the **effective radius** shall not exceed a limit $a_{\max}$ that depends on the details of the actual measurement as described in Annex J.

If it is not possible to follow this requirement, a larger **hydrophone** radius may be used in one particular situation, namely in the Type II measurement, if the two **hydrophones** to be compared have the same **effective radius** value within ± 5 %.

If these two requirements are not fulfilled, a theoretical correction may, if possible, be applied to the results obtained, but this shall be clearly stated and explained and a reference for the formulas used shall be given.

Annex A (informative)

Assessment of uncertainty in free field calibration of hydrophones

A.1 General

To be truly meaningful, the result of a calibration should be accompanied by its associated uncertainty. In evaluating and expressing the uncertainty in the calibration, the guidance provided by the ISO *Guide to expression of uncertainty in measurement* (ISO GUM) [3] shall be followed. In general, uncertainty components are grouped according to how the values are estimated:

Type A: evaluated by statistical means;

Type B: evaluated by other means.

A.2 Overall (expanded) uncertainty

The overall uncertainty should be obtained from all uncertainty components in the manner described in the ISO GUM [3].

When combining uncertainty components, care should be taken when component values are expressed in decibels. Before combination, the values should ideally be expressed in linear form (e.g. in per cent or in the units of the quantity) and not in decibels. The final value of expanded uncertainty may be expressed either in the units of the quantity, in per cent or converted to decibels as required.

NOTE 1 It should be realized that the use of decibels to express uncertainties may lead to asymmetric distributions (e.g. +1,5 dB is equivalent to +19 %, but –1,5 dB is equivalent to –16 %).

NOTE 2 When each component of uncertainty is small, i.e. less than 1 dB, the overall uncertainty can be calculated using decibels.

A.3 Common sources of uncertainty

The following is a list of common sources of uncertainty in the calibration of hydrophones. This list should not be considered exhaustive, but may be used as a guide when assessing uncertainties for a specific implementation of a calibration method. Depending on the calibration method chosen and its implementation, some (though possibly not all) of these sources will require assessment. For example, the errors from measuring instruments might be minimized by the use of the same measuring channel (amplifier, filter, voltmeter, etc.) for all signals and measuring only amplitude ratios. However, since this might not be the case in all implementations, components for these sources of error have been included in the list.

Sources of uncertainty specific to free field reciprocity calibrations:

- inaccuracy of any assumptions about the acoustic field, for example that the field is a spherical-wave field;
- errors in the measurement of the separation distance;
- errors in the values for acoustic frequency;
- errors in the values for water density.

Sources of uncertainty specific to comparison calibrations:

- errors in the calibration of the reference hydrophone (a major source of error in a comparison calibration);
- short-term instability of any reference transducers used for comparison calibrations (e.g. instability of the output of a transducer used as a reference source in a comparison calibration);
- instability of the reference hydrophone in comparison calibrations (i.e. variation in sensitivity of reference hydrophone since previous absolute calibration);
- differences in environmental conditions for the comparison calibration compared with those that existed during the absolute calibration of the reference hydrophone, which would cause a change in sensitivity for the reference hydrophone (e.g. temperature, soaking, details of hydrophone mounting, etc.);
- inaccuracy of any assumptions about the acoustic field produced by a reference source, for example that the field is a spherical-wave;
- errors in positioning of the hydrophones at the same point within the acoustic field;
- lack of stability in the reference transducer electrical drive conditions, including lack of linearity if it is driven with a signal different to that used in its own absolute calibration;
- differences in environmental conditions for the comparison calibration compared with those that existed during the absolute calibration of the reference transducer, which would cause a change in sensitivity for the reference transducer (e.g. temperature, length of soaking period, details of mounting).

Sources of uncertainty common to all of the above methods:

- interference from acoustic reflections, leading to a lack of free field conditions;
- lack of acoustic far field conditions;
- the spatial averaging effects of the hydrophones under calibration due to their finite size and the lack of perfect plane wave conditions;
- misalignment, particularly at high frequencies where the hydrophone response can be far from omnidirectional;
- acoustic scattering from the hydrophone mount (or vibrations picked up and conducted by the mount);
- errors in measurement of the received voltage (including the accuracy of the measuring instrumentation – voltmeter, digitizers, etc.);
- inaccuracy of the gains of any amplifiers, filters and digitizers used;
- errors in the measurement of drive current or voltage;
- errors due to the lack of linearity in the measurement system (the use of a calibrated attenuator to equalize the measured signals can significantly reduce this contribution);
- inaccuracy of any electrical signal attenuators used;
- electrical noise including radio frequency pick-up;
- inaccuracy of any electrical loading corrections made to account for loading by extension cables and pre-amplifiers;
- bubbles or air clinging to transducers – this should be minimized by adequate wetting and soaking of transducers;
- environmental conditions, such as water temperature. Corrections need not be included for these if the calibration results specify the conditions and state that the calibration is only valid for the conditions stated.

Annex B (informative)

Behaviour of PVDF polymer sensors in high intensity ultrasonic fields

B.1 General

High intensity ultrasonic fields are commonly used in biomedical ultrasonics and it is now well established that those high amplitude fields lead to ~~non-linear~~ **nonlinear** phenomena including distortion of the waveform and generation of harmonics in the propagation medium [12, 13, 14]. Wideband, calibrated ultrasonic polymer probes of both the membrane and needle type have already proved to be the most suitable **hydrophones** for precise measurements of the ultrasonic fields and basic parameters of the **hydrophones** such as frequency response, **directional response** and voltage sensitivity have been described [15]. However, the information on the linearity of the response of the **hydrophones** is rather limited. Linearity is a topic of particular importance for medical applications; modern diagnostic equipment is capable of generating instantaneous pressure amplitudes on the order of 10 MPa [16]. Such amplitudes are only an order of magnitude lower than those encountered in the focal region of extracorporeal shock wave generators (lithotripters).

In addition, linearity in the pressure response of the **hydrophone** is critical for utilization of ~~non-linear~~ **nonlinear** calibration methods [17].

The tests described below were carried out to determine linearity of ultrasonic **hydrophones** made of PVDF polymer. A partial description of the results discussed was published in [18].

B.2 Theoretical background

The theory of finite amplitude acoustics has many applications in underwater and airborne ultrasound [12]. More recently, the implications of ~~non-linear~~ **nonlinear** propagation phenomena in the biomedical imaging range of frequencies were pointed out [13, 14].

It is well known that the degree of the wave distortion depends on the distance from the source [12]. This relationship provides a practical criterion to distinguish distortions of the waveform due to the ~~non-linear~~ **nonlinear** propagation phenomena, i.e. ~~non-linearity~~ **nonlinearity** of the underlying differential equations and of the propagation medium (here: water). This same practical criterion enables these afore-mentioned distortions to be separated from distortions of the waveform associated with the ~~non-linear~~ **nonlinear** response of the **hydrophone** to the pressure, or possible ~~non-linear~~ **nonlinear** response of the acoustic transmitter or source to voltage excitation. This was used in the tests described below to ensure that the ~~non-linearity~~ **nonlinearity** observed was not associated with a possible ~~non-linear~~ **nonlinear** electroacoustic transfer function.

B.3 Tests

All measurements described here were carried out in a distilled, degassed water at $21,0\text{ °C} \pm 0,1\text{ °C}$. The experimental set-up employed different ultrasound sources working in the frequency range 2,25 MHz to 10 MHz, and **hydrophones**, including needle-type and membrane-type designs [15, 19]. Additionally, an optoacoustic device capable of producing shock waves was used [20, 21]. While the ultrasound sources were able to generate pressure amplitudes on the order of 5,5 MPa [corresponding to instantaneous (spatial-peak temporal-peak) intensities on the order of 1000 W cm^{-2}], the optoacoustic source generated shock waves having peak compressional amplitudes in excess of 10 MPa.

Both sources and **hydrophones** were carefully aligned using an x-y-z micromanipulator system. The signal detected by the **hydrophone** was fed into a spectrum analyzer and then displayed on its screen to determine the harmonic contents. Concurrently, the signal was also observed on an oscilloscope and photographs of the propagating waveforms, corresponding to different axial source distances, were taken.

Prior to each set of measurements, it was verified that the wave distortion was due to the ~~non-linear~~ **nonlinear** propagation phenomena and was not caused due to ~~non-linear~~ **nonlinear** dependence of an acoustic port (transmitting surface) versus excitation voltage. As mentioned above, the verification utilized the fact that the acoustic wave distortion depends on the distance from the source and involved recording the transmitted pulse at different axial distances. Those measurements were performed using both needle-type and unbacked membrane-type **hydrophones** [15, 19].

Three different methods were used to determine the linearity of the response of the **hydrophones** with increasing acoustic pressure.

In the first procedure, the linearity of the needle-type calibrated **hydrophones** was tested by observing the increase in the output voltage of the 0,6 mm and 1 mm diameter probes with increasing excitation of the source transducers. The maximum peak compressional pressure measured by the **hydrophones** in the focal region of the transducers used was approximately 5 MPa at 3 MHz.

The second procedure involved the measurement of the total acoustic power generated by a given source. Calibrated miniature polymer **hydrophones** of the needle and membrane type were used to scan the field and the total power radiated was calculated [22]. The results of the calculations were then compared to the results of the measurements taken at the same field locations with an acoustic radiation force balance. These measurements were performed in the frequency range 1 MHz to 2 MHz to minimize errors due to spatial averaging effects.

The third procedure involved the use of an optoacoustic converter. Earlier work [23, 24 ,25] on more conventional ultrasonic surgical instruments indicated that such a device should produce a diverging field with pressure amplitudes decreasing according to the (distance)⁻¹ law.

NOTE The terms "(distance)⁻¹ law", or "(distance)⁻¹ behaviour", mean that the pressure amplitude behaves in proportion to the reciprocal distance when the distance from the source to the field point considered is increased.

B.4 Results

The linearity measurements described here were carried out using 30 1 mm diameter and 0,6 mm diameter needle-type **hydrophones** [15], and about 10 membrane-type **hydrophones** [15, 19].

In the first procedure, as mentioned above, the linearity of the needle-type calibrated **hydrophones** was tested by gradually increasing the excitation voltage of the 3 MHz source transducer and measuring the corresponding increase in the output voltage of the 0,6 mm and 1 mm diameter needle-type **hydrophones**. A plot of the excitation voltage versus the **hydrophone** signal indicated a linear relationship.

In the second procedure, calibrated miniature polymer **hydrophones** of the needle and membrane type were used to scan the field and the total power radiated was calculated [22]. The results of the calculations were then compared to the results of the measurements taken at the same field locations with an acoustic radiation force balance. For the same acoustic source (either 1,5 MHz or 2,25 MHz) the discrepancy between the acoustic power as measured by the radiation force balance and that determined by using the planar scanning approach was approximately 22 %.

The third procedure involved measurements taken at the output of an optoacoustic converter. In the frequency range 1 MHz to 10 MHz, the waveforms generated by the acoustic sources observed exhibited a shape characteristic for ~~non-linear~~ **nonlinear** propagation phenomena associated with ~~non-linear~~ **nonlinear** properties of the propagation medium. The optoacoustic devices produced waveforms similar to those encountered in the focal region of the commercially available lithotripters. The $(\text{distance})^{-1}$ behaviour of the devices was experimentally confirmed – the maximum pressure amplitude measured was in the order of 10 MPa and the deviation from $(\text{distance})^{-1}$ characteristics was within the experimental **uncertainty** (15 %) [21].

Any discrepancy from the $(\text{distance})^{-1}$ law exceeding the overall **uncertainty** of the measurements would imply a possibility of ~~non-linearity~~ **nonlinearity** in the **hydrophone's** response. However, no such discrepancy was observed with both membrane- and needle-type **hydrophones** [21].

B.5 Conclusions

The linearity of the pressure response for a number of PVDF polymer **hydrophones** was determined. Measurements were performed at the pressure amplitude levels on the order of 10 MPa. Different test procedures were employed and the results obtained using acoustic transducers indicated that the ~~non-linearities~~ **nonlinearities** observed were clearly associated with the wave propagation only. An excellent agreement between the different designs of **hydrophone**, polymer needle-type and unbacked membrane-type, was obtained.

Furthermore, no discrepancy from the $(\text{distance})^{-1}$ law exceeding the overall **uncertainty** of the measurements was observed with both membrane- and needle-type **hydrophones**. As pointed out above, such discrepancy would imply ~~non-linearity~~ **nonlinearity** of the pressure response with increasing acoustic pressure.

The pressure amplitudes in the tests described above were limited to approximately 10 MPa. Additional evidence supporting the results described above emerges from the testing of the specially designed PVDF **hydrophones** for underwater acoustic applications [26, 27]. Negligible changes, within 0,6 dB, in the frequency response of the **hydrophones** were observed up to hydrostatic pressures of 69 MPa.

Based on the results of these preliminary tests and on the information published in [26, 27], it can be concluded that the polymer **hydrophones** show excellent linearity over a range in intensities typical of those encountered in pulse-echo imaging systems [16].

In addition, the pressure-time waveforms measured in the focal region of the lithotripters do not exhibit any unexpected behaviour. The pressures encountered in the focal region of those lithotripters can be on the order of 100 MPa and the shape of the shock waves measured remained unchanged with decreasing excitation voltage or voltage applied to the electrodes in the electrohydraulic system. While this does not constitute a rigorously obtained proof supporting linear response of the PVDF material, on the other hand, there is currently no evidence to indicate that any ~~non-linearity~~ **nonlinearity** in the pressure response of an appropriately designed ultrasonic PVDF **hydrophone** would exist in the range up to approximately 70 MPa.

Annex C (informative)

Electrical loading corrections

C.1 General

The sensitivity of a **hydrophone** is often specified as the **end-of-cable open-circuit sensitivity**. This is the sensitivity of the hydrophone at the end of its cable when not connected to an electrical load. When a specific electrical load, such as an oscilloscope, an amplifier, or an extra cable is used at the output of the hydrophone, the end-of-cable loaded sensitivity of the hydrophone might be related to the end-of-cable open-circuit sensitivity in the following way.

C.2 Corrections using complex impedance

Consider the general case in which the hydrophone is considered as a two-terminal network of complex electric output impedance of a hydrophone, $\underline{Z}_h$, connected to a complex electric load impedance $\underline{Z}_L$. The end-of-cable loaded sensitivity of the hydrophone, M_L , when connected to the specified load, is related to the end-of-cable open-circuit sensitivity, M_c , by:

$$M_L = M_c \sqrt{\frac{\operatorname{Re}(\underline{Z}_L)^2 + \operatorname{Im}(\underline{Z}_L)^2}{[\operatorname{Re}(\underline{Z}_L) + \operatorname{Re}(\underline{Z}_H)]^2 + [\operatorname{Im}(\underline{Z}_L) + \operatorname{Im}(\underline{Z}_H)]^2}} \quad (\text{C.1})$$

where $\operatorname{Re}()$ and $\operatorname{Im}()$ denote the real and imaginary parts of the relevant complex impedance. Often, the electrical load can be assumed to be a parallel combination of a resistance, R_L , and capacitance, C_L . In this case, $\operatorname{Re}(\underline{Z}_L)$ and $\operatorname{Im}(\underline{Z}_L)$ are given by

$$\operatorname{Re}(\underline{Z}_L) = \frac{R_L}{1 + \omega^2 C_L^2 R_L^2} \quad (\text{C.2})$$

and

$$\operatorname{Im}(\underline{Z}_L) = \frac{-\omega C_L R_L^2}{1 + \omega^2 C_L^2 R_L^2} \quad (\text{C.3})$$

where

ω is the circular frequency.

C.3 Corrections using only capacitances

A further simplification is possible if the impedances of both the **hydrophone** and the load can be assumed to be capacitive. This is often a valid assumption for a **hydrophone** at frequencies much less than the resonance frequency and for loads such as extension cables. In this case, if C_H is the end-of-cable capacitance of the hydrophone including any integral cable and connector, the above equation reduces to

$$M_L = M_c \left[\frac{C_H}{C_H + C_L} \right] \quad (\text{C.4})$$

Annex D (informative)

Absolute calibration of hydrophones using the planar scanning technique

D.1 Overview

This annex provides a detailed description of the methodology relating to the calibration of hydrophones using the planar scanning technique. It provides guidance on the options for mechanical scanning of the hydrophone and on evaluating important sources of calibration uncertainty.

D.2 Hydrophone scanning methodology

There are several ways of scanning a **hydrophone** over the plane $z = l$ in the ultrasonic beam. The most comprehensive is to obtain a rectangular array of sample points by moving the **hydrophone** in a two-dimensional raster scan. In this case:

$$\iint \overline{[U_L(x, y, l, t)]^2} dy dx \approx \sum_{m=1}^M \sum_{n=1}^N \left[\overline{U_L(x_m, y_n, l, t)} \right]^2 \Delta y \Delta x \quad (\text{D.1})$$

where

M and N are the number of sample points in the y and x directions, respectively; and
 Δx and Δy are the step sizes in the x and y directions respectively.

An alternative scanning procedure is possible if the beam profile from the transducer can be assumed to be approximately cylindrically symmetrical. In this case, a number of **diametrical beam scans** may be performed. These scans should pass through the ultrasonic **beam centre** and be spaced at equal angular increments. For example, if two scans are performed, they should be at 90° to each other. For N **diametrical beam scans** we have:

$$\iint \overline{[U_L(x, y, l, t)]^2} dy dx \approx \left(\frac{\pi}{N} \right) \sum_{i=1}^N \left\{ \sum_{r=R_{1i}}^{R_{2i}} [U_L(l, r)]^2 r \Delta r + [U_L(l, s)]^2 \left(\frac{\Delta r}{2} - s \right)^2 \right\} \quad (\text{D.2})$$

where

r is the distance of each scan point from the ultrasonic **beam centre** (equal to $(y^2 + x^2)^{1/2}$ if the **beam centre** is chosen at the origin of the y, x coordinate system);
 Δr is the step size;
 R_{1i} and R_{2i} are the distances from the **beam centre** to the extremes of the i th **diametrical beam scan**;
 s is the distance from the ultrasonic **beam centre** to the nearest scan point.

The second term on the right-hand side of equation (D.2) represents the contribution to the total integral from the ultrasonic **beam centre**.

NOTE Equation (D.2) does not assume that a scan point coincides with the **beam centre** or that scan points are equally spaced from the **beam centre**.

D.3 Corrections and sources of measurement uncertainty

D.3.1 Total power

For the measurements referred to in Clause 10, the **hydrophone** is positioned at a distance $z = l$ from the transducer, in which case a correction to the total ultrasonic output power emitted by the transducer, P_o , (assumed to be at $z = 0$) shall be made for the attenuation of the water path using the expression:

$$P(l) = P_o \exp(-2\alpha z) \quad (\text{D.3})$$

where

P_o is the total ultrasonic output power emitted by a transducer;

$P(l)$ is the total power in the ultrasonic beam at the hydrophone;

α is the amplitude attenuation coefficient of plane waves in a medium (usually water).

Annex E provides values for the temperature- and frequency-dependent attenuation for use in equation (D.3).

There are three sources of **uncertainty** in the value for the total power in the ultrasonic beam at the hydrophone $P(l)$ and an estimate should be made of each one. First, there is the systematic uncertainty in the determination of the total output power, P_o , either from a standard transducer or from a transducer whose output power has been measured using the radiation force measurement technique (see IEC 61161).

The second source of uncertainty is due to possible differences between the total output power from the transducer during the beam scanning procedure and the measured or assumed (for a standard transducer) output power. The magnitude of this uncertainty can be estimated from previous knowledge of the stability of the transducer. This uncertainty should be determined separately for each transducer that is used.

The final source of uncertainty in the determination of total power arises from the correction for the attenuation of water. Uncertainties occur both in the attenuation coefficient α/l^2 , which should be taken as $\pm 1,7$ % at all temperatures (see [28] and [29]), and also in the determination of the distance, l , between the transducer and the hydrophone. This separation may be determined by measuring the time delay recorded on an oscilloscope between the excitation of the ultrasonic transducer and the reception of the signal at the **hydrophone**.

D.3.2 Received hydrophone signal

The magnitude of the **hydrophone** signal $U_L(x,y,l,t)$ is generally determined using an oscilloscope, digitizer or any other appropriate system, and the uncertainty in the measurement of this signal should be determined. The uncertainty will depend on the harmonic content of the **hydrophone** signal, the frequency response of the hydrophone and the method used to determine the **hydrophone** signal.

It has been shown that planar scanning undertaken on distorted waveforms leads to significant calibration errors [30]. These errors are largest if the peak-positive acoustic peak is used for measuring the **hydrophone** signal and decrease if either the peak-to-peak or peak-rarefactional acoustic pressure is used.

D.3.3 Integration

It is essential to have adequate sampling of the beam in the planar scanning technique. For diametrical beam scans, and assuming cylindrical symmetry, it can be shown using an analysis similar to that in [28] provided that there are at least seven sample points between (and including) the two points 6 dB below the peak of the acoustic pressure beam profile (or five points between the 6 dB points on the pressure squared profile), the uncertainty in the

hydrophone sensitivity arising from the numerical integration is less than $\pm 1\%$. If a raster scanning technique is used, it can be shown that, if both M and N in equation (D.1) are chosen such that both the beam scans passing through the beam centre in the y and x directions contain at least seven sample points between (and including) the two points 6 dB below the peak of the acoustic pressure beam profile, the uncertainty in the hydrophone sensitivity arising from the numerical integration is less than $\pm 1\%$. An assessment shall be made of the uncertainty caused by a finite number of sample points.

In the case of **diametrical beam scans**, the assumption of cylindrical symmetry may be tested by analyzing the data from each radial part of the scan separately in the formula

$$\sum_{j=0}^{j_{\max}} [U_L(l, r_j)]^2 r_j \Delta r \quad (\text{D.4})$$

where

r_j is the distance from the **beam centre** to the scan point;
 $j_{\max}$ is the number of the farthest scan point in a radial scan.

NOTE It is assumed here that each diametrical scan has been decomposed into two radial (or half scans), with the data being analysed separately.

The percentage difference between the maximum and minimum of these values shall be determined and one-half of this value shall be used to determine the uncertainty introduced from the assumption of cylindrical symmetry when **diametrical beam scans** are used.

D.3.4 Directional response

A correction for the directional response of the **hydrophone** shall be made by calculation unless the directional response of the **hydrophone** is not predictable. In the latter case, the procedure shall be to alter the angle of the **hydrophone** to obtain maximum output voltage at each point in the scan. It might not be necessary to optimize the rotation for each scan position, especially if the separation between sample points represents a small change in the angle of incidence of the ultrasound on the **hydrophone**. The procedure based on calculation shall be as follows. First, the directional response of the **hydrophone** should be determined at the frequency, f . Let the normalized directional response function be $D(\theta_1)$, where θ_1 represents the angular orientation. To correct the measurements referred to above, the **hydrophone** signal $U_L(x, y, l, t)$ shall be divided by the factor $D(\theta_1)$, where $\theta_1 = \arctan [(x^2 + y^2)^{1/2}/l]$.

Methods of determining the directional response of **hydrophones** are specified in 12.5.

D.3.5 Finite size of the hydrophone

An estimate shall be made for the uncertainty caused by the finite size of the active element of the **hydrophone**. A **hydrophone** responds to the integral of the acoustic pressure over its active element, and therefore a correction for spatial averaging may be necessary [5, 7, 31, 32, 2]. An estimate of the magnitude of this correction shall be obtained by calculating the difference between the acoustic pressure at a point in the field and the pressure averaged over the **hydrophone** surface ([2], IEC 62127-1). For the purposes of this calculation, the effective area of the **hydrophone** shall be used to define the extent of the **hydrophone** surface. The effective area can be determined from the **effective radius** of the **hydrophone** active element, which shall be determined using the procedures specified in 12.5 [6]. Contributions to the integrations in the planar scanning process [equation (10)] are largest from the centre of the beam; therefore, it is only necessary to determine the uncertainty and apply a correction for regions near the centre of the ultrasonic beam. It is usually preferable to perform measurements at a distance l from the transducer such that the spatial averaging effect at the centre of the beam is less than 5 %.

D.3.6 Noise

In general, the **hydrophone** is scanned to a distance from the ultrasonic **beam axis**—~~centre~~ until no signal is observed above the noise. To apply a correction to the integral of the square of the **hydrophone** signal to account for the contribution from the noise, the noise level shall first be determined. The noise level shall be determined by repeating the whole scanning process with the transducer turned off and measuring the rms noise level at each point. The rms noise level, $U_n(x,y,l)$, shall be subtracted from the measured signals in the following manner. If the average value of the square of the **hydrophone** signal is

$$\overline{[U_L'(x,y,l,t)]^2} \quad (D.5)$$

then the average value of the **hydrophone** signal after correcting for the contribution from noise is

$$\overline{U_L(x,y,l,t)^2} = \overline{[U_L'(x,y,l,t)]^2} - U_n^2(x,y,l) \quad (D.6)$$

With the **hydrophone** at the distance corresponding to the limit of the planar scanning process, an ultrasonic signal below the noise level might be present. In this case, the magnitude of the contribution from outside the scanning region (that omitted in the integration) shall be determined using a theoretical model of the ultrasonic beam. In the **far field** region of a circular plane piston source, the pressure at a point R is proportional to:

$$2J_1(ka_t \sin \theta) / (ka_t \sin \theta) \quad (D.7)$$

where

k is the circular wave number;

a_t is the effective or geometrical radius of the ultrasonic transducer;

θ is the angle between the line connecting the point R to the centre of the transducer and the **beam axis**, see also Clause 4;

J_1 is a Bessel function of the first kind of first order.

This model assumes a spherical scan and hence the contribution omitted shall be determined by integration of this theoretical distribution (squared) over a spherical region defined from the edge of the planar scanning region and compared with the total integral over a hemisphere. The contribution to the integral from outside the scanning region in the planar scanning procedure shall be assumed to be the same as that obtained from the spherical scan model. This contribution shall be used as a correction to the integration, and an uncertainty equal to the correction shall be assigned. This uncertainty is usually small compared to other components.

It might be preferable to scan out to a certain threshold below the peak signal at the centre of the ultrasonic beam, for example 10 % [26] or 5 % [33]. In this case, the contribution from outside the scanning region will be significant and a correction factor shall be determined by using the same procedure as given above.

NOTE 1 The geometrical radius of the ultrasonic transducer may be used instead of the effective radius if the latter is not known.

NOTE 2 The significance of the contribution due to noise to the integration depends on the method of measurement of the **hydrophone** signal.

D.3.7 ~~Non-linear~~ Nonlinear propagation

The planar scanning technique determines the sensitivity of a **hydrophone** at a particular frequency f . It is important that the ultrasonic wave used is not distorted by the introduction of high frequency components due to ~~non-linear~~ nonlinear propagation. For the