INTERNATIONAL STANDARD

IEC 62092

First edition
2001-08

**Ultrasonics – Hydrophones –
Characteristics and calibration in the
frequency range from 15 MHz to 40 MHz**

*Ultrasons – Hydrophones –
Caractéristiques et étalonnage dans la gamme
de fréquences de 15 MHz à 40 MHz*

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International Electrotechnical Commission 3, rue de Varembé Geneva, Switzerland
Telefax: +41 22 919 0300 e-mail: inmail@iec.ch IEC web site http://www.iec.ch

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ULTRASONICS – HYDROPHONES – CHARACTERISTICS AND CALIBRATION IN THE FREQUENCY RANGE FROM 15 MHz TO 40 MHz

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.
3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.
5) The IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards.
6) Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 62092 has been prepared by IEC technical committee 87: Ultrasonics.

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

FDIS	Report on voting
87/203A/FDIS	87/209/RVD

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

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

Annexes A, B, C, D and E are for information only.

The committee has decided that the contents of this publication will remain unchanged until 2006. At this date, the publication will be

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

INTRODUCTION

The spatial and temporal distribution of acoustic pressure in an ultrasonic field in a liquid medium is commonly determined using miniature ultrasonic **hydrophones**. The characteristics and calibration of these **hydrophones** have been dealt with in a number of IEC standards in the frequency range 0,5 MHz to 15 MHz. The purpose of this International Standard is to extend this frequency range up to 40 MHz. The main **hydrophone** application in this context is the measurement of ultrasonic fields emitted by medical diagnostic equipment in water. It has turned out in recent years that **hydrophone** operation in the frequency range above 15 MHz is important to characterize fully this equipment, primarily due to the increased appearance of high-frequency components in the ultrasonic signals, caused by nonlinear propagation. In addition, the number of medical ultrasonic systems which use frequencies above 15 MHz, particularly intra-operative probes, is growing.

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 which is used today in various areas of medical ultrasonics and particularly 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 prescriptions of this International 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 International Standard or in a separate one.

In agreement with present measurement practice, **hydrophones** are dealt with in this International Standard as amplitude sensors and not as phase sensors. If phase measurements were to become important in the future, this standard would need revision, with more rigorous requirements being necessary for that kind of measurement.

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

NOTE 2 This International Standard covers the frequency range from 15 to 40 MHz. **Hydrophone** properties and **hydrophone** calibration up to 15 MHz are covered by the International Standards IEC 60866 and IEC 61101. In practice, the useful frequency range of a **hydrophone** may well extend into both frequency ranges, below and above 15 MHz. It has therefore been the aim to keep the regulations of this International Standard as far as possible similar to those of the aforementioned standards. Differences are due either to different technical needs in the respective frequency ranges or to the technical and scientific progress achieved since the publication of the aforementioned standards. At present there are maintenance activities aiming at re-structuring and merging, where possible, all existing **hydrophone** standards. It can be expected that this will lead to unified standards covering the whole field of practical **hydrophone** application.

ULTRASONICS – HYDROPHONES – CHARACTERISTICS AND CALIBRATION IN THE FREQUENCY RANGE FROM 15 MHz TO 40 MHz

1 Scope

This International Standard is applicable to

- **hydrophones** employing piezoelectric sensor elements, designed to measure the pulsed and continuous-wave ultrasonic fields generated by ultrasonic equipment;
- **hydrophones** used for measurements made in water and in the frequency range between 15 MHz and 40 MHz;
- **hydrophones** with or without an integral amplifier;
- **hydrophones** with a circular piezoelectrically active element.

This International Standard specifies

- relevant **hydrophone** characteristics;
- methods of determining **directional response** and **hydrophone** sensitivity based on relative or comparative measurements;

and describes

- absolute **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 International Standard.

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 60866:1987, *Characteristics and calibration of hydrophones for operation in the frequency range 0,5 MHz to 15 MHz*

IEC 61101:1991, *The absolute calibration of hydrophones using the planar scanning technique in the frequency range 0,5 MHz to 15 MHz*

IEC 61102:1991, *Measurement and characterisation of ultrasonic fields using hydrophones in the frequency range 0,5 MHz to 15 MHz*

IEC 61161:1992, *Ultrasonic power measurement in liquids in the frequency range 0,5 MHz to 25 MHz* [1]
Amendment 1 (1998)

IEC 61828:—, *Ultrasonics – Focusing transducers – Definitions and measurement methods for the transmitted fields* [2]

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[1] There exists a consolidated edition 1.1 (1998) that includes IEC 61161 (1992) and its amendment 1 (1998).

[2] To be published.

3 Definitions

For the purposes of this International Standard, the following definitions apply.

3.1
acoustic centre
the 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

[definition 3.3 of IEC 60866]

3.2
beam-alignment axis
used for alignment purposes only, **beam-alignment axis** is a straight line joining two points of spatial-peak temporal-peak acoustic pressure on two hemispherical surfaces whose centres are at the approximate geometrical centre of an ultrasonic transducer or ultrasonic transducer element group. One hemisphere has a radius of curvature of approximately $A_g/\pi\lambda$, where A_g is the geometrical area of the ultrasonic transducer or ultrasonic transducer element group and λ is the wavelength of the ultrasound corresponding to the nominal frequency. The second hemisphere has a radius of curvature either $2A_g/\pi\lambda$, or $A_g/3\pi\lambda$, whichever is the more appropriate. For the purposes of alignment, this line may be projected to the face of the ultrasonic transducer or ultrasonic transducer element group.

For most practical applications, two plane surfaces perpendicular to the direction of propagation of the ultrasound are used. In cases where a unique peak is not located on a hemispherical surface, another hemispherical surface is chosen with a different radius of curvature yielding a unique peak

[definition 3.5 of IEC 61102]

3.3
directional response
directional response of a hydrophone
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 **acoustic centre** and at a specified frequency

[definition 3.12 of IEC 60866]

3.4
effective radius
effective radius of a hydrophone active element
radius of a stiff disc receiver **hydrophone** which has a predicted **directional response** function with an angular width equal to the observed angular width. 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_3 and a_6 respectively

[definitions 3.4 of IEC 61101 and 3.13 of IEC 61102]

Symbols: a, a_3, a_6

Unit: metre, m

3.5
electric load impedance
electric input impedance (consisting of a real and an imaginary part) to which the **hydrophone** unit output cable is connected or is to be connected

Symbol: Z_L

Unit: ohm, Ω

3.6
end-of-cable loaded sensitivity
end-of-cable loaded sensitivity of a hydrophone
ratio of the instantaneous voltage at the end of any integral cable or connector of a **hydrophone**, when connected to a specified electrical input impedance, to the instantaneous acoustic pressure in the undisturbed free field of a plane wave in the position of the **acoustic centre** of the **hydrophone** if the **hydrophone** were removed

[definitions 3.5 of IEC 61101 and 3.14 of IEC 61102, modified]

Symbol: M_L

Unit: volt per pascal, V/Pa

3.7
end-of-cable open-circuit sensitivity
end-of-cable open-circuit sensitivity of a hydrophone
ratio of the instantaneous open-circuit voltage at the end of any integral cable or connector of a **hydrophone** to the instantaneous acoustic pressure in the undisturbed free field of a plane wave in the position of the **acoustic centre** of the **hydrophone** if the **hydrophone** were removed

[definition 3.15 of IEC 61102, modified]

Symbol: M_c

Unit: volt per pascal, V/Pa

3.8
far field
the sound field at a distance from the source where the instantaneous values of the sound pressure and particle velocity are substantially in phase

[definition 3.2 of IEC 60866]

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 International 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).

3.9
hydrophone geometrical radius
geometrical radius of a hydrophone active element
radius defined by the dimensions of the active element of a **hydrophone**

[definition 3.18 of IEC 61102]

Symbol: a_g

Unit: metre, m

3.10
hydrophone
transducer that produces electrical signals in response to waterborne acoustic signals

[See 3.4 of IEC 60866 and 3.19 of IEC 61102]

3.11
hydrophone axis
nominal symmetry axis of the **hydrophone** active element

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 apparent geometrical symmetry axis of the **hydrophone**.

3.12
integral amplifier
active electronic device connected firmly to the **hydrophone** and reducing its output impedance

NOTE 1 An **integral amplifier** requires a supply voltage (or supply voltages).

NOTE 2 The **integral 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.

3.13
pulse duration
1,25 times the interval between the time when the time integral of the square of the instantaneous acoustic pressure reaches 10 % and 90 % of its final value

[definition 3.30 of IEC 61102, modified]

3.14
uncertainty
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

[See 2.2.3 of the ISO/IEC Guide to the Expression of Uncertainty in Measurement [1][3]]

4 List of symbols

a	=	**effective radius** (a_3, a_6: with special reference to a 3 dB or 6 dB definition, respectively)
a_g	=	**hydrophone geometrical radius**
a_{max}	=	maximum **effective radius**
a_t	=	radius of a source transducer
A_g	=	geometrical area of a source transducer
B/A	=	Fox-Wallace non-linearity parameter
c	=	speed of sound in the measurement liquid (water)
e	=	base of natural logarithms
f	=	frequency
f_f	=	fundamental drive frequency of a signal used to generate non-linear distortion
f_u	=	upper frequency limit of the stated frequency band of a **hydrophone**
F	=	geometric focal length of a focusing transducer
k	=	circular wave number
M_c	=	**end-of-cable open-circuit sensitivity**

[3] Numbers in square brackets refer to the bibliography in annex F.

M_L = **end-of-cable loaded sensitivity**

n = harmonic number

p_0 = pressure amplitude

r = path length from the transducer rim to a field point

R = lateral distance from the **beam-alignment axis** (R_{maxE}, R_{maxH}: maximum values with respect to avoiding edge-wave and head-wave interference, respectively)

t_H = arrival time of the nearest head wave

t_{TDS} = time available for a free-field measurement in time delay spectrometry

T = acoustic transmission factor

v_t = speed of a radial wave in a transducer plate

w_f = beam width of the fundamental-frequency field component

x = coordinate along the **beam-alignment axis** and starting from the transducer surface (x_1, x_2, x_3 and x_4 are special distance values according to certain criteria involving edge waves and head waves)

x_{min} = minimum distance for a finite-size **hydrophone** from a transducer

x_{pf} = distance of the pressure focus from a focusing transducer

Δx = distance difference

Z_h = electric output impedance of a **hydrophone**

Z_L = **electric load impedance**

α = small-signal, plane-wave amplitude attenuation coefficient of the measurement liquid (water)

β = non-linearity parameter in the sense of $\beta = 1 + B/(2A)$

γ = ratio of beam diameter to **hydrophone** diameter

δ = pressure amplitude correction for finite **hydrophone** size

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 a 3 dB or 6 dB definition, respectively)

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)

σ, σ_m = non-linear distortion parameter

τ = **pulse duration** or burst duration (τ_{maxE}, τ_{maxH}: maximum values with respect to avoiding edge-wave and head-wave interference, respectively)

ω = circular frequency

5 Hydrophone characteristics

5.1 General

For a full characterization of the **hydrophone** performance in the frequency range of this International Standard, the following information is required.

5.2 Basic information

The following shall be briefly stated:

- the basic physical principles of the transduction process, the type of material involved and the form and geometrical dimensions (diameter, thickness) of the **hydrophone** active element;
- the configuration and design of the **hydrophone**;

NOTE 1 In the case of a membrane **hydrophone**, for example, it is important to know whether the **hydrophone** is of the coplanar or the bilaminar type.

- whether or not an **integral amplifier** is included in the **hydrophone** unit;
- the nominal direction of ultrasonic incidence in relation to the **hydrophone**.

NOTE 2 The last point is important, as it has been found in the literature [2] that even with membrane **hydrophones**, the response may change upon reversal of the ultrasonic propagation direction in relation to the **hydrophone**.

The frequency of the fundamental thickness resonance of the **hydrophone** active element should also be stated.

5.3 Hydrophone class

Since **hydrophones** are used for many different types of measurement, it is not necessary to demand the highest performance specifications for every standard device. Two classes of **hydrophones**, Class 1 and Class 2, to be used for standardized measurement purposes in the frequency range dealt with (15 MHz to 40 MHz) are therefore specified as follows.

The end-of-cable sensitivity level of the **hydrophone** unit (with or without an **integral amplifier**) as a function of frequency shall be constant, over a stated bandwidth of at least one octave in the frequency range from 15 MHz to 40 MHz, with a tolerance of ±2 dB for Class 1 and ±4 dB for Class 2. In addition, it shall not vary by more than ±0,5 dB (Class 1) and ±1 dB (Class 2) within any frequency increment of 1 MHz falling inside the frequency band stated.

NOTE 1 The upper frequency limit of the stated frequency band establishing the class of the **hydrophone** will appear frequently and be referred to as f_u in this International Standard.

NOTE 2 The bandwidth criteria for Class 1 and Class 2 **hydrophones** relate to their ability to measure accurately acoustic fields within which a range of frequency components are present. Typically, but not exclusively, the full quantitative characterization of ultrasonic fields within the frequency range of this standard will require the use of a Class 1 **hydrophone**. In contrast, Class 2 **hydrophones** will be appropriate for use when relative measurements are required, for example in the determination of the spatial characteristics of a field.

NOTE 3 Rather similar **hydrophone** classes having, however, different names, namely Class A and Class B, have been defined in IEC 60866. Note that the two standards cover different frequency ranges and that the class definitions in the two standards therefore do not interfere with each other. If a **hydrophone** whose useful frequency range is sufficiently broad is to be qualified under both standards, four combinations of **hydrophone** classes are possible as follows: Class A + Class 1; Class A + Class 2; Class B + Class 1; Class B + Class 2.

5.4 Sensitivity

The end-of-cable sensitivity of the **hydrophone** unit shall be stated in V/Pa or in decimal submultiples, or as a logarithmic level in dB with reference to a stated sensitivity value.

If an **integral amplifier** contributes to the sensitivity value given, this shall be stated.

NOTE 1 "End-of-cable" refers to the end of the output cable of the **hydrophone** unit, with or without an **integral amplifier**.

It shall be stated whether the sensitivity value given is understood as **end-of-cable open-circuit sensitivity** or as the **end-of-cable loaded sensitivity**. In the latter case, the relevant electric loading conditions shall be stated, i.e. the **electric load impedance** in order to obtain the stated sensitivity.

The **uncertainty** of the stated sensitivity shall be given.

NOTE 2 Table A.1 summarizes overall measurement **uncertainties** of the most widely used calibration techniques.

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

5.5 Frequency response

The **hydrophone** sensitivity as a function of frequency shall be stated either graphically or as a list of values and over a frequency range containing at least the frequency band claimed under 5.3. If it is given as a list of values or as discrete points in a graph, the frequency distance between adjacent points should not be greater than 1 MHz, as far as the frequency range of this International Standard is concerned.

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 statement of the frequency response should refer to the same conditions as the sensitivity statement according to 5.4. If it is understood as referring to different conditions, this shall be clearly stated and formulas shall be given for interrelating the various sensitivities.

If the **uncertainty** of the sensitivity values in the frequency response representation differs from the general **uncertainty** assessment of 5.4, this shall be clearly stated and the new or additional **uncertainty** be given. In case the frequency response is presented graphically only, the additional **uncertainty** due to reading of the graph shall be less than 10 % of the total **uncertainty** listed.

If the frequency response is given as a list of absolute sensitivity values, the sensitivity statement according to 5.4 may be omitted.

NOTE 1 The frequency response and, hence, the **hydrophone** class, may depend on the electric load conditions.

NOTE 2 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.

5.6 Directional response

NOTE 1 The **effective radius** is obtained from the **directional response** (see 5.7). While it is desirable to have the full information, that is, both the **directional response** and the **effective radius**, this may be relaxed in practice to either the **directional response** according to this clause being stated or the **effective radius** according to 5.7.

NOTE 2 For the purposes of this standard, it is assumed that the **hydrophone** active element is nominally circular in geometry. If in the future **hydrophones** of a different geometry appear on the market, this standard will need revision or amendment.

The **directional response** of the **hydrophone** shall be measured and stated at both the lower and upper limits of the frequency band claimed under 5.3, as follows.

The **directional response** shall be measured by rotating the **hydrophone** about an axis which is perpendicular to the **hydrophone axis**, at least from –35° up to +35° (with the **hydrophone axis** as reference) or at least from the first left-hand minimum to the first right-hand minimum, whichever of the angular spans is the lower. This shall be done twice, namely about two rotational axes perpendicular to each other. If in the plane perpendicular to its axis, a **hydrophone** has a certain distinct direction (for example that of the electric leads in the case of a membrane **hydrophone**), the rotational axes should be in this direction and perpendicular to it. The directions of the rotational axes shall be identified on the **hydrophone** or in the accompanying literature.

The two resulting **directional responses** obtained from the two measurements at perpendicular rotational axes shall be given.

If in any of the **directional response** results obtained, the angle between the direction of maximum response and the **hydrophone axis** is greater than 1/10 of the angular difference between the left-hand –6 dB direction and the right-hand –6 dB direction, this shall be stated and the deviation-of-axis angle be given.

NOTE 3 Problems in field measurement practice will arise if the direction of maximum **hydrophone** response varies significantly with frequency.

5.7 Effective radius

From each of the **directional response** results obtained according to 5.6, a value for the **effective radius** of the **hydrophone** active element at both the lower and upper limits of the frequency band claimed under 5.3 shall be derived as follows.

If the angular difference between the left-hand –3 dB direction and the right-hand –3 dB direction is $2\theta_3$ and the angular difference between the left-hand –6 dB direction and the right-hand –6 dB direction is $2\theta_6$, the following formulas for the **effective radii** apply:

$$a_3 = \frac{1{,}62\, c}{2\pi f \sin\theta_3} \tag{1}$$

and

$$a_6 = \frac{2{,}22\, c}{2\pi f \sin\theta_6} \tag{2}$$

where

f is the relevant ultrasonic frequency of the particular measurement;

c is the speed of sound in water at the particular temperature (see table A.2).

If, for the **directional response** in question, a_3 and a_6 are equal to each other within ±10 % (of the maximum value), their arithmetic mean shall be used as the **effective radius**. If not, that value of the two shall be used whose corresponding angle θ is closer to 10°.

If the two **effective radius** values thus obtained for the two measurements at perpendicular rotational axes are equal to each other within ±10 % (of the maximum value), only their arithmetic mean and a statement of this need be given, otherwise both values shall be given.

If in any of the **directional response** results obtained, the angle between the direction of maximum response and the **hydrophone axis** is greater than 1/10 of the angular difference between the left-hand –6 dB direction and the right-hand –6 dB direction, this shall be stated and the deviation-of-axis angle be given, if not done already according to 5.6.

5.8 Dynamic range and linearity

The dynamic range of the **hydrophone**, i.e. the pressure amplitude range in which the **hydrophone** unit (with an **integral amplifier** if included) can be used, shall be given.

This range is to be understood as meeting at least the following conditions:

1. no mechanical or electrical damage to the **hydrophone** or the **integral amplifier**, if included;
2. no output saturation;
3. the output signal must be above the noise level.

NOTE 1 "Output saturation" means that a non-zero pressure increment at the **hydrophone** does not lead to a voltage change.

NOTE 2 The noise level may depend on electromagnetic interference and may thus vary with the electromagnetic conditions at the place of measurement. Ideally, it may be possible to give a noise level representing all other sources of noise except electromagnetic interference.

The range of linearity of the **hydrophone** unit according to 5.1.2 of IEC 60866 should be given.

NOTE 3 Information on **hydrophone** linearity is given in annex B.

5.9 Electric output characteristics

All quantitative values in this clause are understood with the **hydrophone** in water under free-field conditions.

5.9.1 Electric output termination

It shall be stated which of the following two subclauses applies (i.e. 5.9.1.1 or 5.9.1.2).

5.9.1.1 Matched impedance

If the output impedance is matched to the characteristic impedance of the output cable (which is typically low in comparison with 1 kΩ):

The **electric load impedance** to which the output cable is to be connected shall be given. It is required in this case that all sensitivity statements according to this standard are understood as **end-of-cable loaded sensitivities** with reference to this impedance.

Limits for this impedance should be given such that the actual sensitivity agrees with the stated one within a stated maximum error or within the **uncertainties** given under 5.4 and 5.5.

NOTE 1 This may be done in practice as follows. A lower and an upper limit for the load resistance (embracing the characteristic impedance value) are given and an upper limit for the capacitance parallel to the resistance is given.

NOTE 2 This subclause normally applies if an **integral amplifier** is included.

NOTE 3 If the input to which the **hydrophone** output cable is connected is a high-impedance one, the requirements of this subclause can usually be met by means of an additional shunt resistance.

5.9.1.2 Unmatched impedance

If the output impedance is not matched to the characteristic impedance of the output cable:

The end-of-cable output impedance Z_h shall be stated as a function of frequency. This can be done by giving the real and the imaginary part or by giving the values of the electrical components (such as resistance and capacitance) of an equivalent network. In the latter case, the type of network must be clearly specified (e.g. the resistance being in series or parallel to the capacitance).

The frequency difference between adjacent frequency points of this statement shall not be greater than 2 MHz, as far as the frequency range of this International Standard is concerned.

The relation between the **end-of-cable loaded sensitivity** and the **end-of-cable open-circuit sensitivity** depends on Z_h and Z_L and is given by

$$M_L = M_c \left\{ \frac{\mathrm{Re}^2 Z_L + \mathrm{Im}^2 Z_L}{\left[\mathrm{Re} Z_h + \mathrm{Re} Z_L\right]^2 + \left[\mathrm{Im} Z_h + \mathrm{Im} Z_L\right]^2} \right\}^{1/2} \quad (3)$$

where "Re" and "Im" are the real and imaginary parts, respectively, of the relevant quantity.

This formula can be used for calculating correction factors if the actual **electric load impedance** does not agree with the conditions stated in connection with the sensitivity values given.

This subclause normally applies if no **integral amplifier** is included.

NOTE Equation (3) applies to a frequency domain consideration. In practical **hydrophone** applications with ultrasonic pulses, time domain considerations (temporal convolution and deconvolution) would have to be taken into account.

5.9.2 Output lead configuration and ringing resonance in cable

The basic configuration of the output leads shall be explained, such as differential output (floating) or unsymmetric output, i.e., single output and ground.

Any electric transmission line with an unmatched termination may under certain conditions give rise to resonance ringing. If this is likely to occur with the **hydrophone** unit in question (either due to the output cable or to an internal transmission line), particularly at the higher frequencies associated with finite amplitude distortion, this should be stated and the ringing frequency to be expected should be given.

5.10 Information on the integral amplifier, if included

The required supply voltage (or supply voltages) and the current consumption shall be stated.

The consequences of supply voltage deviations from the nominal value(s) shall be stated.

All limitations on the amplitude and frequency ranges not given under 5.3, 5.5 and 5.8 shall be stated, such as those due to slew rate limitations etc.

5.11 Environmental and other aspects

5.11.1 Temperature range

The nominal water temperature, its **uncertainty,** and the temperature range over which the given sensitivity applies shall be stated. If possible, a correction accounting for temperatures differing from the stated one should be given, or the sensitivity be given as a function of temperature. If any of the other relevant quantities according to this standard show substantial changes over the usable temperature range, this shall be stated and a correction given.

5.11.2 Water tightness

It shall be stated which parts of the **hydrophone** unit are waterproof and which are not. Limitations, if any, on the duration of water immersion (possibly as a function of temperature) shall be stated.

5.11.3 Water properties and incompatible materials

Limitations, if any, on the water conductivity shall be stated. The water conditions (for example conductivity, gas content) to which all the quantitative statements under this clause (including those under 5.9) refer shall be stated.

Limitations on incompatible materials (e.g. liquids, solutes) shall be stated.

5.11.4 Other aspects

In the case of a membrane **hydrophone**, the reflection and transmission factor (preferably as a function of frequency) should be given.

The user shall be provided with a detailed guidance manual.

6 Relative measurements of hydrophone characteristics

6.1 General concepts

6.1.1 Relative measurement for directional response and for comparison of sensitivity

In this clause two types of measurement are described:

Type I the determination of the **directional response**;

Type II the comparison of sensitivity of two or more **hydrophones**.

Both 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 chiefly 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**.

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** according to 5.6 and the **effective radius** according to 5.7.

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 (according to 5.4) of the **hydrophone** under test, if the sensitivity of the reference **hydrophone** is known (from any calibration), and/or the frequency response (according to 5.5) 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 transducer should not be amplitude-weighted (apodized), i.e., it should as far as possible have a uniform amplitude distribution over its active face.

6.1.2 Temporal waveform and frequency concepts and hydrophone position

All results obtained according to this clause refer to a certain ultrasonic frequency. They are considered as a function of frequency and can basically be understood as amplitudes in a frequency spectrum. This is in contrast to the usual field measurements of diagnostic devices where the relevant quantities are derived from the ultrasonic pulses by mathematical operations in the time domain.

The concepts as regards the temporal waveform and frequency identification are:

a. narrow-band tone burst;

b. broad-band waveform resulting from a narrow-band tone burst after non-linear propagation;

c. broad-band pulse;

d. continuous-wave frequency sweep with time delay spectrometry (TDS).

The concepts regarding the **hydrophone** position in the ultrasonic field are:

A. near-field position;

B. **far-field** position;

C. **far-field** position with special reference to a long propagation path in order to achieve non-linear distortion (in connection with waveform concept b).

The overall aim is to work under plane-wave conditions (see 3.3, 3.6 and 3.7). Assuming a plane-circular transducer, it can generally be said that the field is composed of a plane, direct wave and the non-plane edge wave. According to concept A the **hydrophone** is placed fairly close to the transducer, where as they have different propagation path lengths the two wave components can be separated from each other. By choosing an appropriate time gate the direct, plane ultrasonic pulse can be picked out. According to concepts B and C, on the other hand, the **hydrophone** is placed on the **beam-alignment axis** in the far field. In this region there is only a relatively small path length difference between the two wave components, so they inevitably interfere with each other, but the resulting field character is almost plane, the main restriction being that of a limited diameter of the central lobe of the field.

D. geometric spherical focus position with focusing source transducer (low amplitude or linear excitation);

E. geometric spherical focus position with focusing source transducer (high amplitude excitation).

In cases D or E, the source transducer is focusing so that the beam has the same shape at the geometric focus as that obtained in the **far field** of a nonfocusing transducer. For case D, the advantage of using a focusing transducer as a source is that conditions similar to B are obtained in a shorter path length under linear excitation conditions, thereby reducing attenuation effects. For case E, the field of a focusing transducer at its geometric focus is used to achieve non-linear distortion through high amplitude voltage excitation. The advantages of E are that the attenuation is reduced by the shorter path length for both the fundamental and higher harmonic components of the pressure waveform and the non-linear distortion is obtained by the increased pressure amplitude caused by the focal gain of the transducer.

NOTE 1 Certain combinations of the waveform concepts and the **hydrophone** position concepts are preferred in the literature (although up to now mostly in the frequency range up to 15 MHz or even lower). These are the combinations aB ([3], IEC 60866, and see 5.1.3 of IEC 61102), bC [4, 5], cA [6] and dB [7, 8, 9]. Other combinations are also possible.

NOTE 2 The waveform concepts and the **hydrophone** position concepts are listed again in table A.3.

6.2 Measurement concepts

6.2.1 Source transducer

The ultrasonic source transducer for the measurements described here shall be a circularly symmetric ultrasonic transducer for use in water, either a plane non-focusing transducer for concepts A, B or C or a focusing transducer for concepts D or E. Depending on the waveform concept chosen (see 6.2.3) it must be able to produce the required amplitude and frequency values. This requirement includes the amplifier driving the transducer. The transducer must be temporally stable and it must not lead to a warm-up of the water bath exceeding the acceptable temperature drift limits (see 6.3.2).

The following check is recommended at the beginning of each measurement: in all those cases where bursts or pulses are applied (waveform concepts a, b, c), 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.

6.2.2 Types of measurement

6.2.2.1 Determination of the directional response of a hydrophone (Type I)

The **hydrophone** shall be positioned in the water tank in the field of the source transducer, according to the field position concept chosen (see 6.2.4) and with the **hydrophone axis** aligned with the **beam-alignment axis**. The measurement set-up shall be provided with a mechanical device enabling the **hydrophone** to be rotated about an axis perpendicular to the **beam-alignment axis**, and 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 according to 5.7 which is known after the measurement or can be roughly inferred from equation (2) before the measurement using the **hydrophone geometrical radius**.

It is vital that the **hydrophone** be so rotated that the centre of its active element is kept at the same place in the ultrasound field, in compliance with the positional accuracy requirements of 6.3.3.

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.

The measurement can be conducted in two ways. Either the **hydrophone** output voltage is measured as a function of the rotation angle at a constant frequency; or the **hydrophone** output voltage is measured 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 the data obtained should be rearranged to yield again the **hydrophone** output voltage as a function of the angle of rotation at a constant frequency. The **hydrophone** output voltage measured is divided by that obtained in the orientation of maximum output voltage.

NOTE 2 To give an indication of the angular resolution required, the following assessment is made: assuming a **hydrophone** radius of 0,25 mm and $c = 1488\ \text{m/s}$ for water at 22 °C, the following values are obtained from equation (2): $\theta_6 = 8°$ for a frequency of 15 MHz and $\theta_6 = 3°$ for a frequency of 40 MHz.

NOTE 3 Values for the speed of sound c in water are listed in table A.2.

6.2.2.2 Sensitivity comparison of two hydrophones (Type II)

This involves a series of measurements where the **hydrophones** are placed alternately in the ultrasonic field. The absolute minimum is 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). A series of five or more single measurements would be even better.

In each single measurement the **hydrophone** in question shall be positioned in the water tank in the field of the source transducer and at the relevant place according to the field position concept chosen (see below). The output signal shall be maximized by lateral and rotational adjustment of the **hydrophone**.

It is vital that the centre of the active element of the **hydrophone** in question be positioned in the ultrasonic field exactly at the relevant place chosen for this measurement series, in compliance with the positional accuracy requirements of 6.3.3. The measurement set-up shall be provided with mechanical means making this positioning possible. As an additional, useful procedure it is recommended that the time-of-flight (propagation time) of the ultrasonic burst or pulse be observed as an indicator of the transducer/**hydrophone** distance (not needed for TDS, see 6.2.3.4 and annex E).

The **hydrophone** output voltage is measured as a function of frequency and this is considered in relation to the result obtained with the other **hydrophone**.

If the measurements on the two **hydrophones** are not carried out under the same electric loading conditions, this shall be clearly stated and prescriptions for calculating the **hydrophone** sensitivity ratio for the same loading conditions shall be given.

6.2.3 Temporal waveform concepts

6.2.3.1 Using a narrow-band tone burst (a)

Here, a rectangular, sinusoidal tone burst of fixed frequency f and burst duration τ is applied. The **hydrophone** output voltage does not usually show a clear rectangular burst, but rather a signal with initial and final transients and ideally with a central part of constant amplitude. The burst must be sufficiently long to achieve such a constant **hydrophone** signal amplitude. The constant signal amplitude is measured, e.g. by means of a calibrated oscilloscope. The result obtained refers to the particular frequency chosen.

This concept is characterized by the following features:

- It is a single-frequency method. If the result is desired for several frequencies, the measurement must be repeated at these frequencies. This is time-consuming.
- The frequency range of the source transducer must cover the desired frequency band, therefore in practice it must be a damped, broad-band transducer well suited to the frequency range in question.
- The transducer must produce ultrasonic wave amplitudes high enough to be well above the **hydrophone** noise, taking into account the ultrasonic attenuation along the propagation path.

- If the **hydrophone** output voltage is measured with a broad-band instrument, the harmonic content of the signal must be checked and should be lower than –30 dB in comparison with the fundamental frequency.

NOTE If the harmonic content of the signal is greater than –30 dB, band-pass filtering of the signal at the fundamental frequency or a spectrum analysis of the signal may be used to reduce the content of the second and higher harmonics.

6.2.3.2 Using a broad-band waveform resulting from a narrow-band tone burst after non-linear propagation (b)

A sinusoidal tone-burst of high voltage is applied to the transducer. The ultrasonic signal is propagated over a long distance until a highly asymmetric time waveform is measured by the **hydrophone** at the positions described by either C or E. This distorted waveform is characterized by peaked compressional half-cycles and shallow rarefactional half-cycles and the harmonic content of the spectrum contains equidistant frequencies separated by the fundamental frequency value and with amplitudes which roughly decrease as $1/n$ if n is the harmonic number. The signal received is either fed to a spectrum analyzer or into a fast fourier transform (FFT) calculation stage and the measurement result for a number of discrete frequencies is obtained.

The ultrasonic source itself can be a narrow-band, resonant transducer with a frequency well below the range of interest. However, its frequency should not be too low, as harmonic amplitudes that are high enough must be produced whose frequencies must not be too far removed from the fundamental frequency. For the frequency range of this standard and in view of the requirements of 5.5, the fundamental frequency of this kind of transducer should be in the range of roughly 1 MHz. The transducer must be able to produce pressure amplitudes in the megapascal range, but without producing too much heat, as this would disturb the required temperature stability of the measurement tank (see 6.3.2) and could also lead to an instability of the transducer radiation conductance. These problems can be handled by intermittent operation using a suitable duty factor.

6.2.3.3 Using a broad-band pulse (c)

A short, broad-band pulse of duration τ is produced by the source transducer. The **hydrophone** output signal is again fed to a spectrum analyzer. In this case the frequency resolution of the spectrum amplitude is equal to the reciprocal of the time interval over which the broad-band pulse is measured, and the frequency range covered by the spectrum depends on the pulse produced.

The source transducer can be either a damped, resonant transducer with the main part of the pulse frequency spectrum being around its resonance frequency as determined chiefly by its thickness, which must be low for the frequencies of this standard, or it can be a thick transducer excited by a short current spike as obtained by short-circuiting a high voltage. The main problem in reaching the frequency range of this standard in the latter case is to achieve a rapid switching of high voltages and currents. The thickness of the transducer in the latter case determines the time delay of the arrival of the mechanical pulse radiated at the rear surface of the transducer and disturbing the measurement if this delay is too short.

6.2.3.4 Using a continuous-wave frequency sweep with time delay spectrometry (d)

A continuous-wave signal is used with a linear frequency sweep over the frequency range of interest and at a constant sweep rate. The **hydrophone** output signal is passed through a narrow-band (tracking) filter which is swept synchronously, but with a certain frequency offset in relation to the generator frequency. This frequency offset is adjusted to the time-of-flight (propagation time) of the direct ultrasonic signal from the transducer to the **hydrophone**, the time-of-flight being determined by the transducer/**hydrophone** distance and the speed of sound, which is a function of the water temperature. This technique suppresses the potential influence of reflected signals, strictly speaking all those signals which have a propagation time differing substantially from that of the direct signal.

The main component of the electronic equipment in this case is a special kind of spectrum analyzer able to perform all the relevant operations mentioned. The **hydrophone** output voltage is obtained as a continuous function of frequency. The electronic equipment, particularly the spectrum analyzer, must operate in the frequency range of interest.

The frequency and amplitude requirements with respect to the transducer are the same as those of 6.2.3.1.

6.2.4 Hydrophone position concepts

6.2.4.1 Near-field hydrophone position (A)

The **hydrophone** is positioned fairly close to the transducer (see below) on the **beam-alignment axis**. The direct, plane-wave burst or pulse is picked out from the **hydrophone** output signal by adjusting a time gate.

It is recommended that the suitability of the transducer be checked by observing the **hydrophone** output signal when the **hydrophone** is moved laterally. Ideally the **hydrophone** output signal is independent of the lateral position (in the usable paraxial region, see below), if all parts of the transducer surface vibrate with uniform amplitude and phase.

The geometrical region usable for this type of measurement can be assessed as follows if τ is the burst or **pulse duration**.

6.2.4.1.1 General requirement

The hydrophone distance x should be

$$x \geq \frac{c\tau}{2} \tag{4}$$

so that any pulse reflected from the **hydrophone** to the source and back to the **hydrophone** will not interfere with the end of the pulse initially incident on the **hydrophone**.

6.2.4.1.2 Influence of edge waves

A plane-circular transducer of radius a_t and a field point P at some axial distance x and lateral distance R from the **beam-alignment axis** are considered (see figure 1). The path length of the direct, plane wave is x. The shortest path length of the edge wave is $\sqrt{x^2 + (a_t - R)^2}$, referred to as r in figure 1. The fundamental requirement is that τ must not be greater than the time-of-flight difference between edge wave and plane wave. This leads to the inequality

$$\tau \leq \tau_{\mathrm{maxE}} = \frac{\sqrt{x^2 + (a_t - R)^2} - x}{c} \tag{5}$$

which can be modified to

$$R \leq R_{\mathrm{maxE}} = a_t - \sqrt{(c\tau)^2 + 2c\tau x} \tag{6}$$

this being the inequality defining the paraxial region that can be used.

NOTE Depending on the actual set of parameter values, it may be that the inequality (6) has no solution (which means, formally, that it has a negative solution), in which case this type of measurement is not possible. A remedy would be to reduce the burst or **pulse duration** τ and/or the **hydrophone** distance *x*. The condition for the inequality (6) having a positive solution, which means that this type of measurement is possible, can be formulated as follows:

$$x < x_1 = \frac{1}{2}\left\{\left(\frac{a_t}{c\tau}\right)^2 - 1\right\}c\tau \qquad (7)$$

6.2.4.1.3 Potential influence of head waves

The plane-wave field near the transducer may also be disturbed by waves of another type. These are head waves caused by radial modes which may exist in the transducer during pulse excitation. If a radial wave in the transducer starts at the transducer rim and moves inside at velocity v_t which is assumed to be larger than the speed of sound *c* in the sound-propagating fluid, a field of head waves is radiated into the fluid and may arrive at the **hydrophone** and produce a disturbing output signal, depending on the **hydrophone**'s position, as described e.g. in [10] and [11]. The details depend largely on v_t. As there is usually no *a priori* knowledge about this quantity, no general recommendations can be given here. The practical details should be studied individually and experimentally (see [10]). Annex C gives assessment formulas in analogy to equations (5) and (6), which are helpful if v_t is known.

6.2.4.2 Far-field hydrophone position (B)

NOTE This applies only in connection with waveform concepts a, c and d. For the position type in connection with waveform concept b, see 6.2.4.3.

The **hydrophone** is positioned on the **beam-alignment axis** in the **far field** of the transducer. The **far field** begins at the location of the last axial maximum, which shall be determined for the highest frequency in question, and this distance is to be regarded as the minimum distance for the **hydrophone** position in this case.

For a theoretical, plane-circular piston source the last axial maximum is at a distance $x = a_t^2 f/c$. This distance is proportional to the frequency, and so in the frequency range of this standard appreciable distance values may result, depending on the transducer radius. However, the propagation path length should not generally exceed values of a few decimetres in order to avoid as far as possible the consequences of ultrasonic attenuation, and so source transducers with a sufficiently small diameter must be chosen in this case.

6.2.4.3 Far-field hydrophone position with special reference to a long propagation path in order to achieve non-linear distortion (C)

In connection with waveform concept b given in 6.2.3.2, the propagation path must be sufficiently long to achieve both significant non-linear distortion of the waveform and also ensure that the acoustic pressure distribution is sufficiently broad so that spatial-averaging effects are maintained below a specified level (see 6.3.4.4). This can be achieved using relatively large diameter plane-piston transducers whose near-field distance ($a_t^2 f/c$) may be in the range 200 mm to 400 mm [4]. The degree of non-linear distortion occurring at the position of the **hydrophone** may usefully be characterized by the non-linear distortion parameter σ whose value depends on the pressure amplitude at the source (p_0) and for plane waves is given by

$$\sigma = 2\pi \frac{\beta p_0 f_f x}{\rho c^3} \qquad (8)$$

where

$\beta = 1 + B/(2A)$ is the non-linearity parameter for water (approximately 3,5 with values for the Fox-Wallace parameter *B*/*A* being given in [12], for example);

f_f is the fundamental drive frequency of the source which is used to generate the non-linear distortion;

x is the propagation distance;

ρ is the density of water.

For optimum comparison conditions, the value of σ should be 3, a situation which corresponds to a non-linear loss of 6 dB in the amplitude of the fundamental [13]. For this value of σ, the waveform takes on the appearance of the classical saw-tooth, with spectral harmonic amplitudes varying as 1/*n* where *n* is the harmonic number. Using these properties, it is useful to evaluate the pressure amplitude generated at high frequencies as this will affect the accuracy of any calibration. Assuming that the $\sigma = 3$ condition holds (i.e. the pressure amplitude at the field position is 50% of the pressure amplitude, p_0, at the source), the pressure amplitude generated at the upper limit of the **hydrophone**'s frequency band (f_u) can be readily derived as $0{,}5\ p_0\ f_f/f_u$ (essentially, the ratio f_f / f_u is equivalent to 1/*n*, where *n* is the harmonic number corresponding to the upper frequency band of the hydrophone).

NOTE For water at 22 °C, equation (8) leads to $\sigma = 6{,}7\ p_0\ f_f\ x$ where

p_0 is in MPa;

f_f is in MHz;

x is in m.

These approximate expressions are intended for guidance, and assume plane-wave and lossless propagation. The self-focusing behaviour of piston sources can be taken into account to provide a more accurate treatment [13]. The lossless propagation condition is valid providing the parameter $\sigma/(\alpha x)$ is $>> 1$, where α is the small-signal attenuation coefficient of the water, which is proportional to the square of the frequency (and values of which are given in table A.2). This criterion is more generally fulfilled at lower fundamental frequencies, for example at 1 or 2 MHz. At higher frequencies ($\sigma/(\alpha x) \cong 1$) small-signal attenuation of the fundamental will limit the distortion and therefore reduce the harmonic content in the field.

In any implementation of this method, it is recommended that the frequency content of the axial non-linear field of the transducer should be investigated to establish the optimum comparison position(s) subject to the requirements imposed by 6.3.4.4. These position(s) should maximize the signal-to-noise ratio for frequencies up to f_u.

6.2.4.4 Geometrical spherical focus position with focusing source transducer (D) (low voltage or linear excitation)

NOTE 1 This applies only in connection with waveform concepts a, c, and d. For the position type in connection with waveform concept b, see 6.2.4.5.

The **hydrophone** is positioned on the **beam-alignment axis** at the geometric spherical focus of the focusing source transducer. If the geometric focal length, *F*, of the transducer is not known, it can be determined from x_{pf}, the distance of the pressure focus (which is the position of the maximum pulse-pressure-squared-integral along the beam axis) from the transducer, and the formula

$$F = \left(\frac{1}{x_{pf}} - \frac{c}{f a_t^2} \right)^{-1} \qquad (9)$$

NOTE 2 The distance from the transducer surface is referred to as z in IEC 61828 instead of x.

For linear excitation conditions the non-linear propagation parameter σ_m (3.25 of IEC 61102) for focusing transducers must be less than 1.

6.2.4.5 Geometric spherical focus position with focusing source transducer and high voltage excitation in order to achieve non-linear distortion (E)

The **hydrophone** is positioned on the **beam-alignment axis** at the geometric spherical focus of the focusing source transducer. If the geometric focal length, *F*, of the transducer is not known, it can be determined from the location of the pressure focus under linear excitation conditions as described in 6.2.4.4 above. To achieve sufficient non-linear distortion, the non-linear propagation parameter σ_m should be 3 or greater.

6.3 Requirements

6.3.1 Measurement vessel and water

The measurement vessel must be large enough to allow the **hydrophone** to be positioned in the ultrasonic field according to the positioning concept chosen and to allow the **hydrophone** to be rotated in a measurement of type I (see also IEC 60866 and IEC 61102).

Degassed, distilled (or deionized) water shall be used. Water conductivity limitations and other limitations according to 5.11 must be observed, including possible limitations on the duration of the **hydrophone**'s immersion in water. The **hydrophone** should be immersed in water prior to measurements for a time sufficient to ensure its soaking is complete. All air bubbles and particularly the adherence of air bubbles to the **hydrophone** must be avoided.

The measurement vessel should have an absorbent lining material although this is not absolutely necessary, as in the measurement concepts of this standard the consequences of echoes are to a great extent suppressed by means of time gates or time delay spectrometry. In the particular case of concept bC, oblique baffles should be used on the tank walls to prevent glancing reflections [4].

6.3.2 Temperature stability

The water temperature shall be constant to within ±0,5 °C during the measurement.

NOTE Temperature drifts are to be avoided for three reasons.

1. The **hydrophone** sensitivity may depend on the temperature (see 5.11).
2. 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 table A.2).
3. 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 table A.2). This is of relevance to the adjustment of the time gate for bursts or pulses and also to time delay spectrometry.

With respect to point 2 the following example can be given. If a plane ultrasonic wave in the linear amplitude range is propagated over 15 cm at a temperature around 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 table A.2).

With respect to point 3 the following recommendation can be made: in a measurement of type II, the axial **hydrophone** distance should be adjusted to a constant propagation time.

For a list of decibel (dB) values compared with amplitude ratios, see table A.4.

6.3.3 Positional accuracy

This subclause deals with the accuracy of the relative positioning of two **hydrophones** or of one **hydrophone** under various angles of rotation.

6.3.3.1 Accuracy of the axial hydrophone position

The axial distance of the centre of the **hydrophone** active element from the transducer shall be constant to within ±0,2 mm. This requirement may need modification in case of focusing source transducers and depending on their actual axial field distribution.

NOTE 1 For focusing source transducers operating in the frequency range of this International Standard, positioning is critical. The following is an assessment of the axial distance change from the focal length, i.e., $\Delta x = F - x$, leading to a pressure reduction of 1 dB. Starting from the theoretical equation $\sin[\xi(1/x - 1/F)]/[\xi(1/x - 1/F)] = 0{,}891$ from the annex of IEC 61828, where $\xi = \pi a_t^2 f/(2c)$, a two-term sine expansion yields $\Delta x = 0{,}808\, F^2/\xi$.

NOTE 2 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 0,2 mm apart differ by 0,01 dB for a frequency of 15 MHz and by 0,07 dB for a frequency of 40 MHz, as a consequence of the frequency-dependent attenuation (see table A.2).

6.3.3.2 Accuracy of the lateral hydrophone position

It is recommended that the dependence of the **hydrophone** output voltage be checked when the lateral **hydrophone** position is varied. The condition for the **hydrophone** lateral 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 $R = 0{,}107\, cx/(f a_t)$ for a 0,5 dB amplitude reduction and $R = 0{,}151\, cx/(f a_t)$ for a 1 dB amplitude reduction.

6.3.4 Maximum hydrophone size

6.3.4.1 General

In order to avoid measurement errors in the measurements described here, the **effective radius** shall not exceed a limit a_{max} that depends on the details of the actual measurement as described below.

If it is not possible to follow this rule, it is permissible to use a larger **hydrophone** radius 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.

6.3.4.2 Maximum hydrophone size in the near-field case (A)

If the near-field position concept according to 6.2.4.1 is chosen, the maximum **hydrophone** radius is in principle only limited by the radius of the usable paraxial region in the sense of 6.2.4.1 or annex C. If, however, the recommended lateral displacement check shows amplitude variations, these should be less than ±1 dB for a **hydrophone** displacement by an amount equal to the **effective radius** in all lateral directions.

6.3.4.3 Maximum hydrophone size in the far-field case (B)

For an assessment a simple formula based on linear propagation in the **far field** of a plane-circular piston source and obtained from 5.1.5 of IEC 61102 can be given as

$$a_{max} = \frac{cx}{8 f a_t} \qquad (10)$$

NOTE 1 Strictly, this formula applies only if $x >> a_t$ and $x << 20 f a_t^2 / c$ (see [14]), but this is generally fulfilled in the measurements dealt with in this subclause.

NOTE 2 In [14] a theoretical correction procedure has been derived, to multiply the measured pressure amplitude by $(1+\delta)$ in order to obtain the true pressure amplitude, where δ is given by $\delta = [\pi a/(16 a_{max})]^2$ with a_{max} as in equation (10). This applies only to the **hydrophone** standard orientation, i.e., with the **hydrophone** surface perpendicular to the field axis.

NOTE 3 Equation (10) may also be used in case D.

6.3.4.4 Maximum hydrophone size in the far-field case with special reference to a long propagation path in order to achieve non-linear distortion (C)

The waveform at the field point used for the comparison consists of a number of harmonic frequencies and the pressure distribution of each needs to be sufficiently broad to ensure that spatial-averaging over the **hydrophone** element does not degrade the calibration accuracy providing. With a prudent choice of transducer diameter and propagation distance plane-wave conditions over the effective receive aperture of the **hydrophone** may be approximated.

As the higher harmonics have beamwidths which progressively decrease with increasing frequency, spatial-averaging will be more important at the upper frequency limit f_u. An estimate of the effect of spatial-averaging may be made by considering the highest frequency harmonic beam-width using a parameter γ, given by

$$\gamma = (-6 \text{ dB beam-width of } f_u \text{ component}) / (\text{effective hydrophone diameter}) \qquad (11)$$

NOTE 1 The beam-widths referred to in the expression are measured values, and, providing $\gamma > 2$, measured and actual (true) beam-widths may be considered to be equivalent. The condition of $\gamma = 2$ corresponds to a spatial-averaging correction of 7,5 %.

A spatial-averaging error of less than 3,5 % requires $\gamma > 3$. Reducing the permissible error to 2 %, requires $\gamma > 4$ [15].

NOTE 2 From 5.1.5 of IEC 61102 the recommended maximum radius of the **hydrophone** is given by $a_{max} = cx/(8 f a_t)$. Taking $x = a_t^2 f / c$, this corresponds to a γ value of approximately 2,8.

Simple guidelines establishing the experimental conditions required to limit the effect of spatial-averaging to this specified level may be derived. Two assumptions are made during the analysis:

- the beamwidth of the fundamental component under the non-linear conditions used for the comparison is identical to that derived from linear propagation;

NOTE 3 Changes in the pressure distribution occur at progressively high values of σ leading to a broadening of the beam profile of the individual harmonics [16]. The current analysis therefore represents a worst case.

- the harmonic beamwidths are given by $w_f / \sqrt{n}$, where w_f is the beamwidth of the fundamental component and *n* is the harmonic number [17].

If f_f is the fundamental frequency and f_u is the upper frequency limit for the calibration, then assuming an ideal plane-piston transducer, an expression may be derived for x_{min}, the minimum distance between the transducer and **hydrophone** required to keep the effect of spatial-averaging below the specified level. The expression for x_{min}, valid for large values of ka_t, is

$$x_{min} = 0{,}451 \gamma a k a_t \sqrt{\frac{f_u}{f_f}} \qquad (12)$$

where

a is the **effective radius;**

$k = 2\pi f_f / c$ is the fundamental circular wave number;

a_t is the radius of the transmitting transducer.

Equation (12) may be used to derive approximate values of x_{min} although due to non-linear broadening, smaller distances may actually be used.

In any implementation of the concept bC method, the frequency content of the waveform must be investigated at various positions off-axis, in order that the influence of frequency dependent spatial averaging be estimated using available models ([15], for example).

NOTE 4 Equation (12) can also be solved for *a* yielding the maximum **hydrophone** radius at a given distance *x*.

6.3.5 Requirements for the electronic equipment

6.3.5.1 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 ±0,1 %.

6.3.5.2 Receiving electronics

The signal from the **hydrophone** or **integral amplifier** 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 **integral amplifier** also may be necessary.

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 input impedance must be known so that the **end-of-cable loaded sensitivity** can be determined.
- Its frequency response must be known over a frequency range which contains at least the frequency band claimed under 5.3.
- Its linearity with input signal over a dynamic range of 50 dB shall be better than ±0,3 dB.
- In case of a digital signal analyzer: For recording temporal waveforms, the sampling rate shall be at least $20 \times f_u$ megasamples/second, where f_u is in MHz. Also, the gain shall be adjusted to allow at least seven significant bits in the digitized waveform.

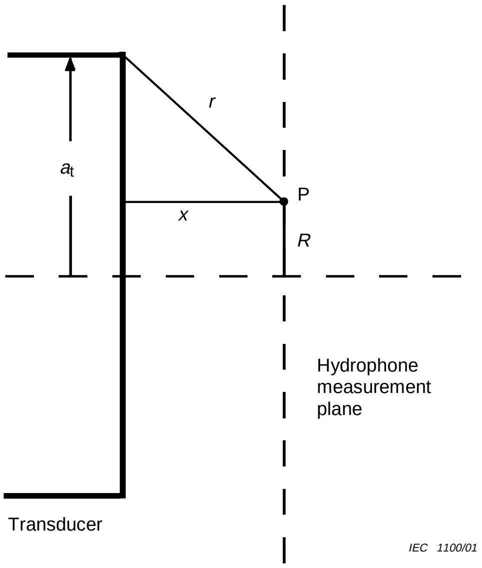
6.3.6 Requirements with particular respect to time delay spectrometry

For time delay spectrometry no requirements are formulated. Guidance can be found in annex D and [7, 8, 38, 39].

7 Hydrophone calibration

The **hydrophone** shall be calibrated according to one of the state-of-the-art calibration methods.

NOTE See annex E for examples of current technology methods in the frequency range of this International Standard.



Key

x axial distance from the transducer

R lateral distance from the field axis

r propagation path length of the edge wave

Figure 1 – Coordinates of a field point P in the near field of a plane-circular source transducer of radius a_t

Annex A
(informative)

Tables

Table A.1 – List of typical uncertainty values obtained by the calibration methods given in this standard and for the frequency range dealt with here

Line	Method	Frequency range	Uncertainty
1	Absolute calibration (interferometry) according to annex E.3.1	up to 30 MHz	±13 %
2		up to 40 MHz	±15 %
3	Absolute calibration (interferometry) according to annex E.3.2	up to 20 MHz	±7 %
4		up to 30 MHz	±10 %
5		up to 40 MHz	±11 %
6	Absolute calibration (reciprocity/TDS) according to annex D and E.4.1	up to 30 MHz	±14 %
7		up to 40 MHz	±21 %
8	Substitution calibration (see below)	up to 20 MHz	±9 %
9		up to 30 MHz	±12 %
10		up to 40 MHz	±14 %
11	Substitution calibration (see below)	up to 30 MHz	±16 %
12		up to 40 MHz	±22 %

The **uncertainties** in the list are understood at a level of confidence of 95 %. Lines 8 to 10 cover a substitution calibration where the reference **hydrophone** has been calibrated according to E.3.2 (lines 3 to 5 of the list) and the sensitivity comparison has been made according to method bC type II of Clause 6. Lines 11 and 12 cover a substitution calibration where the reference **hydrophone** has been calibrated according to annex D and E.4.1 (lines 6 and 7 of the list) and the sensitivity comparison has been made according to method dB type II of Clause 6. Note that in both cases, the **uncertainties** of the absolute calibration and of the sensitivity comparison have been combined in quadrature.

Table A.2 – Speed of sound *c* [18, 19] and linear amplitude attenuation coefficient α divided by the frequency squared ([20], interpolated), as a function of the temperature, in water

Temperature °C	***c*** m s^{-1}	$\frac{\alpha}{f^2}$ m^{-1} MHz^{-2}
20	1 482	0,025
23	1 491	0,023
26	1 499	0,021
NOTE If the amplitude attenuation coefficient in m^{-1} is to be given in dB m^{-1}, its numerical value has to be multiplied by $20 \times \lg e = 8{,}69$.		

Table A.3 – List of the waveform concepts and the hydrophone position concepts

<table>
<tr><td colspan="2">Temporal waveform concepts</td><td colspan="2">Hydrophone position concepts</td></tr>
<tr><td>a</td><td>Narrow-band tone burst</td><td>A</td><td>Near-field position</td></tr>
<tr><td>b</td><td>Broad-band waveform from narrow-band tone burst after non-linear propagation</td><td>B</td><td>Far-field position</td></tr>
<tr><td>c</td><td>Broad-band pulse</td><td>C</td><td>Far-field position with long propagation path to achieve non-linear distortion</td></tr>
<tr><td rowspan="2">d</td><td rowspan="2">Continuous-wave frequency sweep with time delay spectrometry</td><td>D</td><td>Geometric spherical focus with focusing source transducer (linear propagation)</td></tr>
<tr><td>E</td><td>Geometric spherical focus with focusing source transducer (non-linear propagation)</td></tr>
</table>

Table A.4 – List of decibel (dB) values and the corresponding amplitude ratios

dB	Amplitude ratio	dB	Amplitude ratio
0,01	1,001	–0,01	0,999
0,07	1,008	–0,07	0,992
0,09	1,010	–0,09	0,990
0,2	1,023	–0,2	0,977
0,3	1,035	–0,3	0,966
0,5	1,059	–0,5	0,944
0,7	1,084	–0,7	0,923
1	1,122	–1	0,891
1,5	1,189	–1,5	0,841
2	1,26	–2	0,79
3	1,41	–3	0,71
6	2,00	–6	0,50

Annex B
(informative)

Behaviour of PVDF polymer sensors in high intensity ultrasonic fields

B.1 Introduction

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 phenomena including distortion of the waveform and generation of harmonics in the propagation medium [21-23]. 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 [24]. 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 [25]. 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 calibration methods [26].

The tests described below were carried out to determine linearity of the ultrasonic **hydrophones** made of PVDF polymer. Partial description of the results discussed was published in [27].

B.2 Theoretical background

The theory of finite amplitude acoustics has many applications in underwater and airborne ultrasound [21]. More recently the implications of non-linear propagation phenomena at the biomedical imaging range of frequencies were pointed out [22, 23].

It is well known that the degree of the wave distortion depends on the distance from the source [21] and this relationship provides a practical criterion to distinguish distortions of the waveform due to the non-linear propagation phenomena i.e. non-linearity of the underlying differential equations and of the propagation medium (here: water) and to separate them from distortions of the wave associated with the non-linear response of the **hydrophone** to the pressure or possible non-linear response of the acoustic transmitter or source to voltage excitation. This procedure was used in the tests described below to ensure that the non-linearity observed was not associated with a possible non-linear electroacoustic transfer function.

B.3 Experimental

All measurements described here were carried out in a distilled, degassed water at 21,0 °C ± 0,1 °C. The experimental set-up employed different ultrasound sources working in the frequency range 2,25 MHz – 10 MHz, and **hydrophones**, including needle-type and membrane-type designs [24, 28]. Additionally, an optoacoustic device capable of producing shock waves was used [29, 30]. While the ultrasound sources were able to generate pressure amplitudes on the order of 5,5 MPa (corresponding to instantaneous (sptp) intensities on the order of 1 000 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 polaroid pictures 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 propagation phenomena and was not caused due to non-linear dependence of an acoustic port (transmitting surface) vs. 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** [24, 28].

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

In the first method, 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 [31]. 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 [32-34] on more conventional ultrasonic surgical instruments indicated that such device should produce a diverging field with pressure amplitudes decreasing according to the $(\text{distance})^{-1}$ law.

NOTE The term "$(\text{distance})^{-1}$ law" or "$(\text{distance})^{-1}$ behaviour" means 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 thirty 1 mm diameter and 0,6 mm diameter needle-type **hydrophones** [24], and about ten membrane-type **hydrophones** [24, 28].

In the first method, 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 [31]. 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 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 propagation phenomena associated with non-linear 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 on the order of 10 MPa and the deviation from $(\text{distance})^{-1}$ characteristics was within the experimental **uncertainty** (about ±15 %) [30].

Any discrepancy from the $(\text{distance})^{-1}$ law exceeding the overall **uncertainty** of the measurements would imply a possibility of non-linearity in **hydrophones** response. However, no such discrepancy was observed with both membrane and needle **hydrophones** [30].

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 methods were employed and the results obtained using acoustic transducers indicated that the non-linearities 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 **hydrophones**. As pointed above, such discrepancy would imply non-linearity of the pressure response with increasing acoustic pressure.

The pressure amplitudes in the experiments 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 [35, 36]. 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 testings and on the information published in [35, 36] 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 [25].

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 may be on the order of 100 MPa and the shape of the shock waves measured remains 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 indicating that any non-linearity in the pressure response of an appropriately designed ultrasonic PVDF **hydrophone** would exist in the range up to approximately 70 MPa.

Annex C
(informative)

Hydrophone positioning in the ultrasonic near field

C.1 Head waves near the transducer

Consideration is given to a plane-circular transducer of radius a_t according to figure 1. Consider the conical region (symmetrical with respect to the field axis) whose base is the circular transducer surface and whose apex is the axial point

$$x = x_2 = a_t \sqrt{\left(\frac{v_t}{c}\right)^2 - 1} \qquad \text{(C.1)}$$

where v_t is the wave velocity of radial waves in the transducer. The generating line for this right circular cone is

$$R = a_t - \frac{x}{\sqrt{\left(\frac{v_t}{c}\right)^2 - 1}} \qquad \text{(C.2)}$$

For points (x,R) in this region, two head waves will be present, one originating at the nearest point on the source perimeter and one at the furthest [10, 11]. On axis these head waves coincide. At all points in this conical region the nearest head wave arrives sooner than the edge wave, so its influence on the usable geometrical region must be considered. Unlike edge waves, head waves are not present at all points in the field. Outside the conical region, head waves either do not exist or arrive later than the edge wave and therefore need not be considered for the purposes of this standard.

Within the conical region defined above, the fundamental requirement when considering head waves is the same as for edge waves; i.e., the burst or pulse duration τ must not be greater than the time-of-flight difference between the nearest head wave and plane wave components. The time of arrival of the nearest head wave, t_H, is

$$t_H = \frac{a_t - R + x\sqrt{\left(\frac{v_t}{c}\right)^2 - 1}}{v_t} \qquad \text{(C.3)}$$

Therefore, in analogy to equations (5) and (6), the condition is

$$\tau \le \tau_{maxH} = \frac{a_t - R - x\left\{\frac{v_t}{c} - \sqrt{\left(\frac{v_t}{c}\right)^2 - 1}\right\}}{v_t} \qquad \text{(C.4)}$$

from which

$$R \le R_{\text{maxH}} = a_{\text{t}} - v_{\text{t}}\tau - x\left\{\frac{v_{\text{t}}}{c} - \sqrt{\left(\frac{v_{\text{t}}}{c}\right)^2 - 1}\right\} \qquad \text{(C.5)}$$

The inequality (C.5) has positive solutions if

$$x < x_3 = \frac{a_{\text{t}} - v_{\text{t}}\tau}{\frac{v_{\text{t}}}{c} - \sqrt{\left(\frac{v_{\text{t}}}{c}\right)^2 - 1}} \qquad \text{(C.6)}$$

C.2 Statements on the usable paraxial plane-wave region in the case of a near-field hydrophone position, considering both edge wave and head wave contributions

Assume that a **hydrophone** is positioned at an axial distance x from a plane-circular transducer of radius a_{t} (according to figure 1) emitting a burst or pulse of duration τ. The time-of-flight criteria lead to the following statements, depending on the actual value of x in relation to four reference values the first three of which have been given as x_1, x_2 and x_3 in equations (7), (C.1) and (C.6), and the fourth of which is defined by

$$x_4 = \frac{\sqrt{\left(\frac{v_{\text{t}}}{c}\right)^2 - 1}}{\frac{v_{\text{t}}}{c} - \sqrt{\left(\frac{v_{\text{t}}}{c}\right)^2 - 1}}\, c\tau \qquad \text{(C.7)}$$

A complete set of different cases is given in the following:

1. If $x \ge x_1$, the type of measurement considered here is not possible due to a violation of the edge wave time-of-flight condition.
2. If $x < x_1$ and $x \ge x_2$, the measurement is possible and the usable paraxial region is given by inequality (6).
3. If $x < x_1$ and $x < x_2$ and $x \ge x_3$, the measurement is not possible due to a violation of the head wave time-of-flight condition.
4. If $x < x_1$ and $x < x_2$ and $x < x_3$ and $x \ge x_4$, the measurement is possible and the usable paraxial region is given by inequality (6).
5. If $x < x_1$ and $x < x_2$ and $x < x_3$ and $x < x_4$, the measurement is possible and the usable paraxial region is given by inequality (C.5).

It should be noted that the **hydrophone**'s whole sensitive area must be in the usable paraxial region so that R includes both the **hydrophone** radius plus, possibly, the lateral distance of the **hydrophone** centre from the field axis.

It should also be noted that all the statements above are subject to the general requirement of inequality (4).

Annex D
(informative)

Time delay spectrometry – Requirements and a brief review of the technique

D.1 Introduction

Time delay spectrometry (TDS) was originally proposed [37] for analysis of loudspeaker behaviour in acoustically reflective environments. Later, it was suggested for calibration of the **hydrophones** in the megahertz frequency range [7]. A comprehensive analysis of the TDS technique [38] reviews and examines in depth all space and instrumentation requirements needed for practical implementation of the TDS technique. A combination of TDS and reciprocity [8] has been used for absolute calibration of **hydrophones** and a number of experimental data are presented in [39]. The figure of merit in terms of frequency resolution has also been considered [31].

In this annex, the most important requirements of the TDS technique and its relevant parameters are briefly reviewed.

D.2 Calibration and performance evaluation of ultrasonic hydrophones using time delay spectrometry

D.2.1 Ultrasonic field parameter measured

The primary parameter measured when using the TDS technique is acoustic pressure. The pressure amplitude is recorded concurrently with the electrical voltage produced at the hydrophone terminals. The ratio of the voltage and its corresponding pressure yields the end-of-cable loaded sensitivity as a continuous function of frequency.

D.2.2 Ultrasonic frequency range over which the technique is applicable

The technique is used in audible acoustics range from about 20 Hz and in biomedical ultrasonics from 1 MHz to 40 MHz. The technique has also been successfully implemented from 100 kHz to 1 MHz.

Limitations:

1. frequency range of the measurement equipment available;
2. in the case of a substitution calibration, availability of calibrated reference **hydrophones** in the frequency range of interest.

D.2.3 Ultrasonic field configuration for which the technique is applicable

Plane waves (continuous-wave and swept).

D.2.4 Spatial resolution

The output signal represents the frequency spectrum of the measured temporal signal. The range resolution depends on the ratio of the filter bandwidth to the sweep rate used. **Uncertainty** in the frequency resolution of the performed measurement can, in general, be expressed as $f = 1/t_{TDS}$, where f is the frequency in hertz, and t_{TDS} is time available for a free field measurement in seconds. Both frequency response and directivity patterns can be readily obtained by using the TDS technique, see examples in [7, 8, 31, 38, 39].

D.2.5 Sensitivity of technique

Depends on the input signal available from the **hydrophone** being tested. At acoustic pressure amplitudes as low as 1 kPa, a typical signal-to-noise ratio of approximately 50 dB can be achieved. The maximum achievable signal-to-noise ratio is on the order of 75 dB. Typically, changes of about 0,2 dB in the **end-of-cable loaded sensitivity** can be detected.

D.2.6 Range over which the sensitivity is measured

End-of-cable loaded sensitivity or **end-of-cable open-circuit sensitivity** down to approximately –300 dB re 1 V/µPa (1×10^{-9} V Pa^{-1}) can be measured readily.

D.2.7 Reproducibility

Typical: <±5 % (in the range 0,1 MHz to 10 MHz) for sensitivities >3×10^{-9} V Pa^{-1}. Achievable: approximately 2 %.

D.2.8 Impulse response

Can be obtained from a Fourier transform of the frequency response if the phase of the TDS signal is recorded. The resolution of the impulse response is commensurate with the frequency range recorded [40].

D.2.9 Procedure for performing measurements

Consult [7, 8, 31, 38, 39] for a typical measurement arrangement. The procedures are briefly given as follows.

D.2.9.1 Measurement procedure (sensitivity intercomparison)

1. Position and align transducer (transmitter) and receiver (previously calibrated **hydrophone** [24, 41, 42]) in a degassed, distilled water bath, controlled to ±0,5 °C.
2. Measure logarithmic spectrum in the selected frequency range.
3. Store measured spectrum (frequency response) in memory.
4. Replace known ultrasonic **hydrophone** with a **hydrophone** to be calibrated.
5. Repeat steps 1, 2, and 3.

NOTE 1 Positioning can be done as follows: Verify that the **hydrophone** to be calibrated is in the same field position as the known **hydrophone** by either (1) pulsing the transmitter and adjusting the axial distance so that the pulse propagation delay is the same for both **hydrophones**, and then moving the **hydrophone** laterally to maximize the signal; or (2) with the TDS time delay set the same as for the known **hydrophone**, positioning the **hydrophone** to be calibrated so that its signal is maximized.

6. Plot difference of both logarithmic spectra. (If the reference **hydrophone** has a flat frequency response, the difference represents the frequency response of the **hydrophone** being calibrated.) See [7, 8, 31, 38, 39] for details.

NOTE 2 The TDS technique can be used both in performing sensitivity intercomparisons and absolute (reciprocity) calibration. See [8, 31] for details. However, for the sensitivity intercomparison, a reference **hydrophone** having a known frequency response as a continuous function of frequency is required.

D.2.9.2 Measurement procedure (reciprocity calibration)

Reciprocity calibration requires use of a fairly complex measurement set-up and special equipment. More specifically, a wideband bridge circuit to decouple the transmit and receive signals and wideband transducer dummy load are needed. Instead of a dummy load, two identical transmitters can be used. See [8, 31] for details. The measurement **uncertainty** of the combined reciprocity/TDS technique has been reported to be less than 10 % in the frequency range 2 MHz – 15 MHz. Below 2 MHz and above 15 MHz the **uncertainty** increases to approximately 20 %, primarily due to the signal-to-noise ratio available.

D.3 Limitations

One basic limitation of the TDS technique is the assumption that the propagation medium is non-dispersive. This does not pose any practical difficulty as the **hydrophone** calibration is carried out in degassed and deionized water.

Annex E
(informative)

The absolute calibration of hydrophones up to 40 MHz

E.1 Overview

This informative annex describes the current status of absolute methods of calibration for ultrasonic **hydrophones** appropriate for frequencies above 15 MHz. The basis of some of the methods which have been used in the past, as well as those currently under evaluation, are briefly described in E.2. These are based on the non-linear propagation of plane-waves and optical interferometry. The latter method in particular is attractive, as calibrations may be made directly traceable to primary standards of length measurement. This annex also describes the progress made in implementing absolute calibration methods based on optical interferometry at two National Standards Laboratories. The fundamental difference between the two implementations, designated I and II in E.3.1 and E.3.2, lies in the disposition of the acoustic and laser beams. In implementation II, in direct contrast to implementation I, the optical beam traverses the acoustic beam. Other calibration methods are briefly described in E.4.

NOTE "Absolute" **hydrophone** calibration is understood here in the sense of "without reference to another **hydrophone**". This is sometimes also referred to as "primary" calibration. On the other hand, **hydrophone**s 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**. This annex E deals with the former procedure. The latter procedure is dealt with in detail in Clause 6. It should be noted that a substitution calibration usually involves both steps and that the interested user should refer to both Clause 6 and this annex E (and that **uncertainties** from both fundamental steps contribute to the final calibration **uncertainty** in the case of a substitution calibration).

E.2 Present position

E.2.1 'Magnomic' or non-linear propagation based method

In the past, work has been undertaken to calibrate **hydrophones** at frequencies as high as 100 MHz using the so-called "magnomic" method [43]. This utilises a non-linear propagation model for plane-waves and exploits the fact that, for a piston transducer of relatively large diameter, suitable time-gating of the acoustic signal can isolate the plane-wave component from the edge-wave radiated from the piston edge. At high-pressure amplitudes, these plane-waves undergo finite amplitude distortion, producing an acoustic field rich in harmonics. A theoretical plane-wave propagation model is used to predict the distortion of these sound waves, and by comparing the predictions with measurements made close to the face of the transducer (undistorted) and at a known distance further along the axis (distorted and made harmonically rich by non-linear propagation), a calibration of the **hydrophone** can be obtained at each harmonic frequency.

Results obtained from this method were promising and agreed well with the theoretical response of two membrane **hydrophones.** It does, however, have some disadvantages. Firstly, it depends crucially on the propagation model used. Secondly, the method depends on the performance of the transducer used to generate the acoustic field. Owing to transducer imperfections, the field produced may deviate significantly from the desired plane-waves, leading to significant **uncertainties** in the calibration.

Methods employing a smaller diameter focusing transducer to generate harmonics in a focal plane overcome some of these disadvantages. Measured fields are more reproducible at a known focal length distance where there is a well-defined main beam lobe. The focal gain of the transducer can provide higher pressures full of harmonics in a shorter distance than distances used for the plane wave approach. Suitable focusing transducers with uniform properties are commercially available.

E.2.2 Optical interferometry

In the calibration method based on optical interferometry, the acoustic field produced by a transducer is detected using a thin plastic membrane (known as a pellicle or foil) metallized on one side to be optically reflecting. The pellicle is thin enough to be acoustically transparent and follows the motion of the acoustic wave, its displacement being measured using optical interferometry, the acoustic pressure being derived from the measured displacement. The **hydrophone** to be calibrated is substituted for the pellicle with the acoustic centre of the **hydrophone** positioned at the same point in the acoustic field interrogated by the laser beam. The **hydrophone** is then calibrated by measuring the output voltage corresponding to the known acoustic pressure.

Clearly, an important requirement for a viable calibration method is that the acoustic pressure is sufficient for the **hydrophone** signal to have an acceptable signal-to-noise ratio at the frequency of interest i.e. up to 40 MHz. However, the optical interferometer actually senses acoustic displacement and this imposes more severe requirements for an acceptable signal-to-noise ratio. For a plane-wave, the acoustic pressure amplitude, p_0, is given by:

$$p_0 = \rho c \omega \zeta \qquad \text{(E.1)}$$

where

ρ is the density of the medium;

c is the speed of sound in the medium;

ω is the circular frequency;

ζ is the amplitude of the acoustic displacement, with the difference in phase between pressure and displacement being ignored.

Ignoring the difference in phase between pressure and displacement means that for a given acoustic pressure, the displacement amplitude is reciprocally related to the frequency so that high acoustic pressures are required to generate a measurable displacement at frequencies of 40 MHz and above. It should be noted that both implementations of the method described below employ focused transducers in order to effect such an increase in acoustic pressure.

E.3 High frequency implementations of optical interferometry

E.3.1 Implementation I

E.3.1.1 Measurement system

The optical calibration technique is based on measurement of the displacement of a membrane which is positioned at the surface of a liquid containing a transducer (figure E.1). The generated sound wave is normally incident and displaces the membrane which is measured using a Michelson interferometer [44-47]. It contains a laser as a light source and a polarizing beam splitter for dividing and combining the optical field (figure E.1). In the measuring arm the light is focused onto the foil which is coated with an aluminium layer in order to improve the optical reflectivity. The focusing ensures a small spot diameter for a sufficient spatial resolution.

A balanced photodetection scheme with a bandwidth $BW \approx 100$ MHz detects the optical output field. It consists of two photodiodes and a difference transimpedance amplifier A_V suppressing amplitude noise and increasing the photocurrent. The transimpedance amplifier is followed by a second amplifier V. It has a high input impedance and can be used as a **hydrophone** amplifier (see below). The interferometer is path-stabilized [45] by a servo-loop with a unity-gain frequency of about 100 Hz. In this case the displacement is obtained from the measured photocurrents by:

$$\zeta = \frac{U_S \lambda_l}{2\pi T \hat{U}} \frac{V(f=0)}{V(f)} \qquad \text{(E.2)}$$

where

λ_l is the wavelength of the light in vacuum;

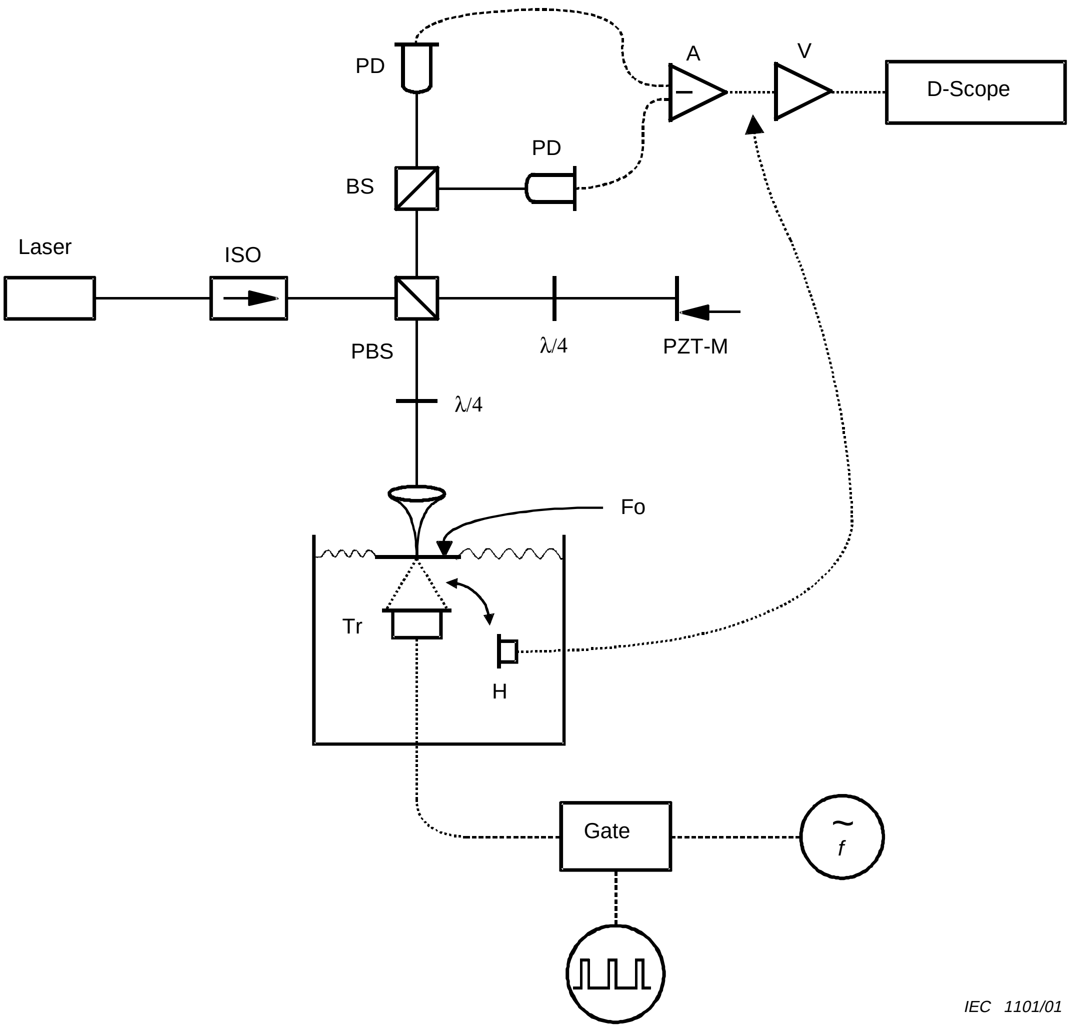
T is the transmission factor of the displacement through the foil;

U_S is the voltage of the signal;

$\hat{U}$ is the peak-to-peak voltage of a complete interferometer fringe measured at the output of the amplifier V which has the frequency dependent gain $V(f)$.

The output voltage, U_S, is detected by a digital scope, i.e. in the time domain with wide bandwidth (BW > 50 MHz). To achieve a sufficiently high signal-to-noise ratio, a focused piezoelectric broad-band transducer is used. It is supplied with a burst of a given frequency and the measurement data are acquired immediately after the onset of the ultrasound when the steady state is reached. This avoids disturbances by reflection at the tank walls.

The alignment is carried out using a three-axis translation and a rotation by two axes. The laser spot is adjusted at the focus perpendicular to the beam axis which is determined by two-dimensional pressure measurements at different distances from the transducer. As alignment criteria the maximum of the interferometer output and the reflected acoustical signal, and the delay time between the excitation pulse and the output signal are sufficient for the translation alignment. The angle between the foil and the sound propagation direction is adjusted using the aligned laser beam as a reference.



Key

PBS	polarizing beamsplitter
ISO	optical isolator
BS	beamsplitter
PD	photodiode
λ/4	lambda-quarter plate
PZT-M	piezo-driven mirror
Tr	acoustical transducer
H	**hydrophone**
A_V	transimpedance amplifier
V	**hydrophone** amplifier
Fo	**foil**
$\tilde{f}$	synthesizer

NOTE λ means the optical wavelength in this figure.

Figure E.1 – Experimental set-up of the interferometric foil technique

After storage of the reference data, the foil is removed and the **hydrophone** in question is fixed at the same place as the laser spot before. A certain amount of water is added to immerse the **hydrophone**. Alternatively the transducer may be rotated as is shown in figure E.1 for simplicity. The **hydrophone** is connected with the input of the amplifier V. Then the measurement is repeated under identical excitation conditions.

The **end-of-cable loaded sensitivity** M_L is obtained by:

$$M_L = \frac{1}{\omega c \rho V(f=0)} \frac{2\pi T \hat{U}}{\lambda_l} \frac{U_H}{U_S} \tag{E.3}$$

where

c is the speed of sound in water;

ρ is the density of water;

U_H is the voltage of the **hydrophone** measurement;

$\omega (= 2\pi f)$ is the circular frequency of the sound field.

Here, the **hydrophone** output is electrically loaded by the input impedance of the amplifier V.

E.3.1.2 Data correction

The determination of the **end-of-cable loaded sensitivity**, M_L, is influenced by three systematic errors which require a data correction using theoretical models:

E.3.1.2.1 Spot diameter

At frequencies higher than 10 MHz, both the **hydrophone** as well as the laser beam focused on the foil can no longer be assumed to be point detectors. Hence, the use of focused transducers leads to spatial averaging effects. To quantitatively describe this effect [46], the transducer is considered as a planar piston. The displacement distribution is obtained from the Fraunhofer diffraction model and the Rayleigh integral solution [47], and all measured average values can be related to the peak pressure values [46].

E.3.1.2.2 Multipass effects in the foil

At the position of the ultrasound focus, the fluid is covered by a coated foil to improve the optical reflectivity. The incident sound field is partially reflected inside the foil and the metallic layer, and this multibeam interference influences the displacement of the foil. Since the phase front at the focus of a sound beam is nearly plane, a simple resonance model [46] using plane-waves can be applied to quantitatively describe the systematic error due to this effect. It yields a transmission factor T for the displacement which is inserted into equations (E.2) and (E.3).

E.3.1.2.3 Frequency response of the photodetector

In contrast to the frequency dependence of the amplifier gain V occurring in both measurements the frequency response of the photodetector influences the **end-of-cable loaded sensitivity** M_L. The bandwidth of high-speed photodetectors, however, is more than 100 MHz and in the frequency range of interest between 0,5 MHz and 40 MHz the response should be nearly flat. Nevertheless, a measurement of the transfer function using an optical mixing oscillator was carried out.

E.3.1.3 Preliminary calibrations

As a first application, fibre tip sensors used in shock-wave measurement were calibrated by the aid of the described technique (for details see [46]). The transfer function of the fibre tip sensor was pointwise determined in the frequency range between 0,5 MHz and 40 MHz. Then the system was extended and improved to handle all kinds of **hydrophones** up to a frequency of 50 MHz. As an example, two membrane **hydrophones** with an active diameter of 0,5 mm were calibrated up to 70 MHz [47]. The overall **uncertainty** of the present calibration system is ±13 % (k = 2) up to 30 MHz and ±15 % (k = 2) up to 40 MHz.

E.3.2 Implementation II

E.3.2.1 Measurement system

The optical interferometric method, developed as a primary standard method of calibrating ultrasonic **hydrophones** over the frequency range 500 kHz to 20 MHz, has been described in detail previously [48] and only a brief description is given here. The technique has been validated for frequencies above 500 kHz by international intercomparison with other National Standards Laboratories [49] and has become well established as a primary standard. A good understanding has been developed of the sources of calibration **uncertainty** with typical overall **uncertainties** for frequencies up to 20 MHz being ±3 % or ±4 % when expressed at a 95 % confidence level.

The pellicles used for the measurements are 3,5 µm and 5 µm thick Mylar® membranes coated with a 25 nm layer of gold. As the optical beam traverses the acoustic beam in this experimental arrangement, the opportunity exists for the two beams to interact. The source of the interaction is the change in refractive index due to local changes in density of the medium in the compressional and rarefactional parts of the acoustic wave. This has implications for the acousto-optic interaction described in E.3.2.4.4.

E.3.2.2 The acoustic field

Calibrations were carried out using focused transducers of nominal centre frequency 5 MHz. Two focal lengths were used in order that some of the systematic **uncertainties** associated with the calibration (acousto-optic, spatial-averaging) be investigated. The nominal focal positions of the transducers were 50 mm and 150 mm. They were driven using tone-bursts of sufficient amplitude to generate strongly non-linearly distorted waveforms at the field position of interest (the focus). In this way, as demonstrated in figure E.2 for a 0,5 mm 9 µm coplanar membrane **hydrophone**, harmonics in the received **hydrophone** waveform were detected up to 100 MHz. The close approximation to an ideal sawtooth should be noted, with the amplitude of successive harmonics showing a close to 1/n dependence in amplitude, where n is the number of the harmonic. Whilst focused transducers need to be applied to generate sufficient acoustic pressures, their use has implications for the corrections, particularly spatial-averaging, where the higher harmonics are of progressively narrower beam-width (see E.3.2.4.3).

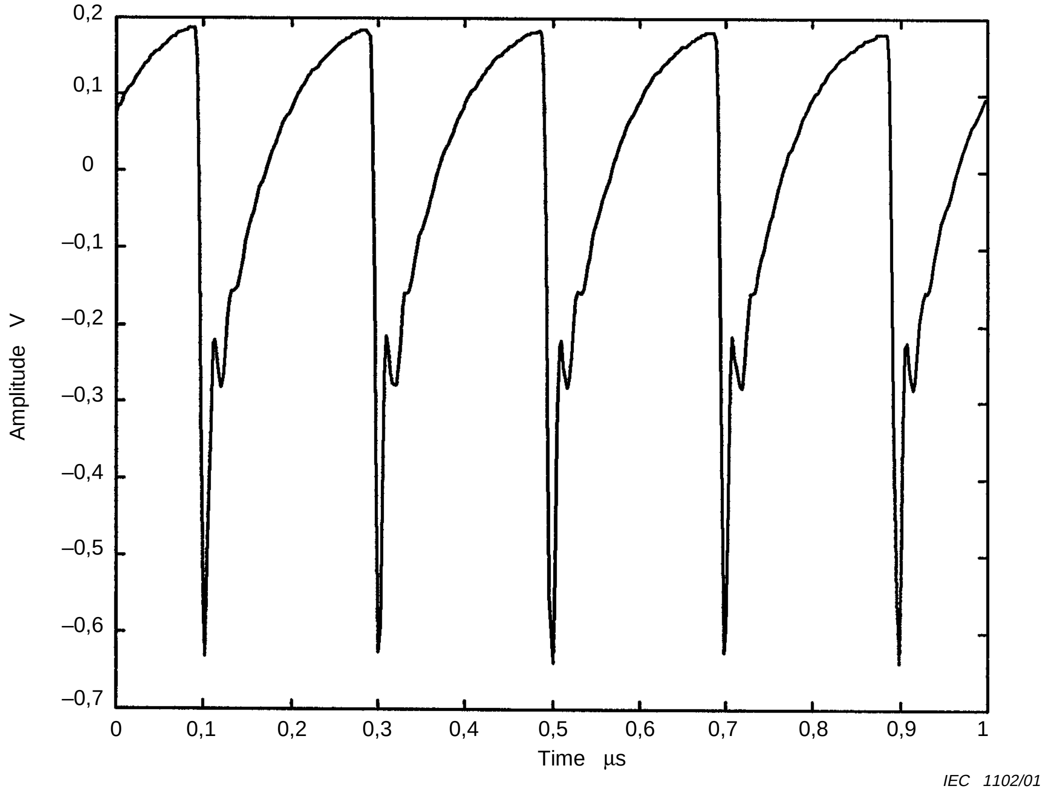


Figure E.2 – Hydrophone waveform generated by a 9 µm coplanar membrane hydrophone positioned at the focus of a 5 MHz transducer (focal length 51 mm)

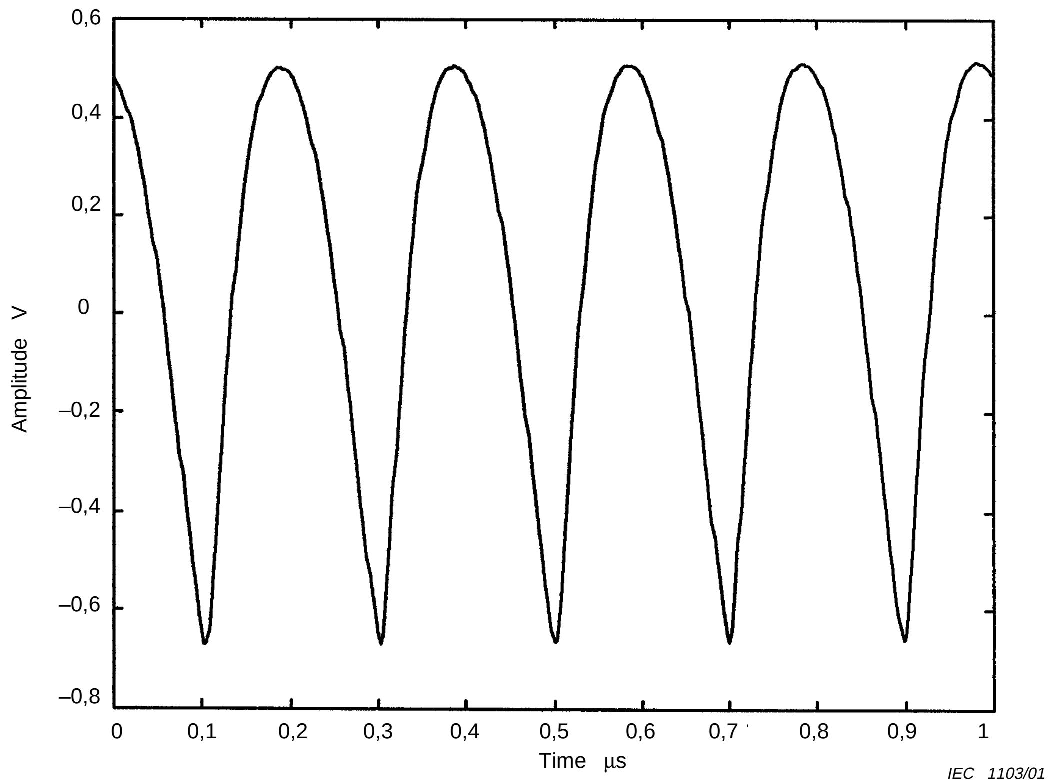


Figure E.3 – Interferometer (displacement) waveform generated with the pellicle positioned at the focus of the 5 MHz transducer (focal position 51 mm)

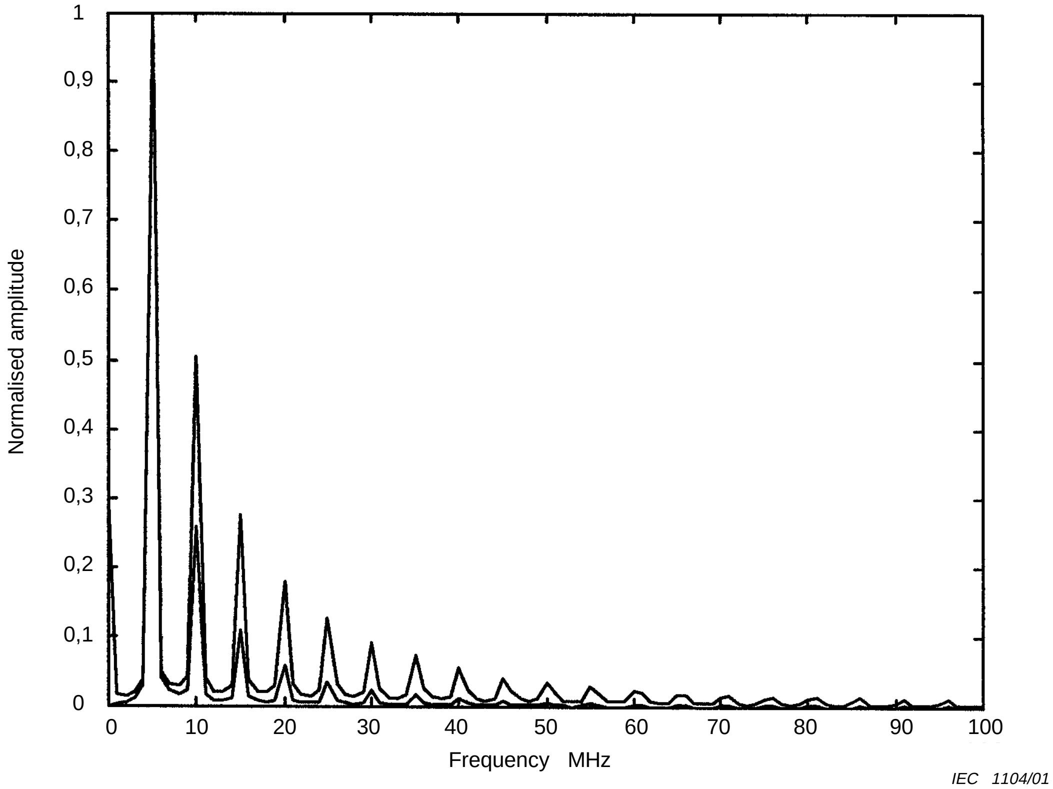


Figure E.4 – Frequency spectrum of the displacement waveform (lower curve) and the differentiated displacement waveform (upper curve)

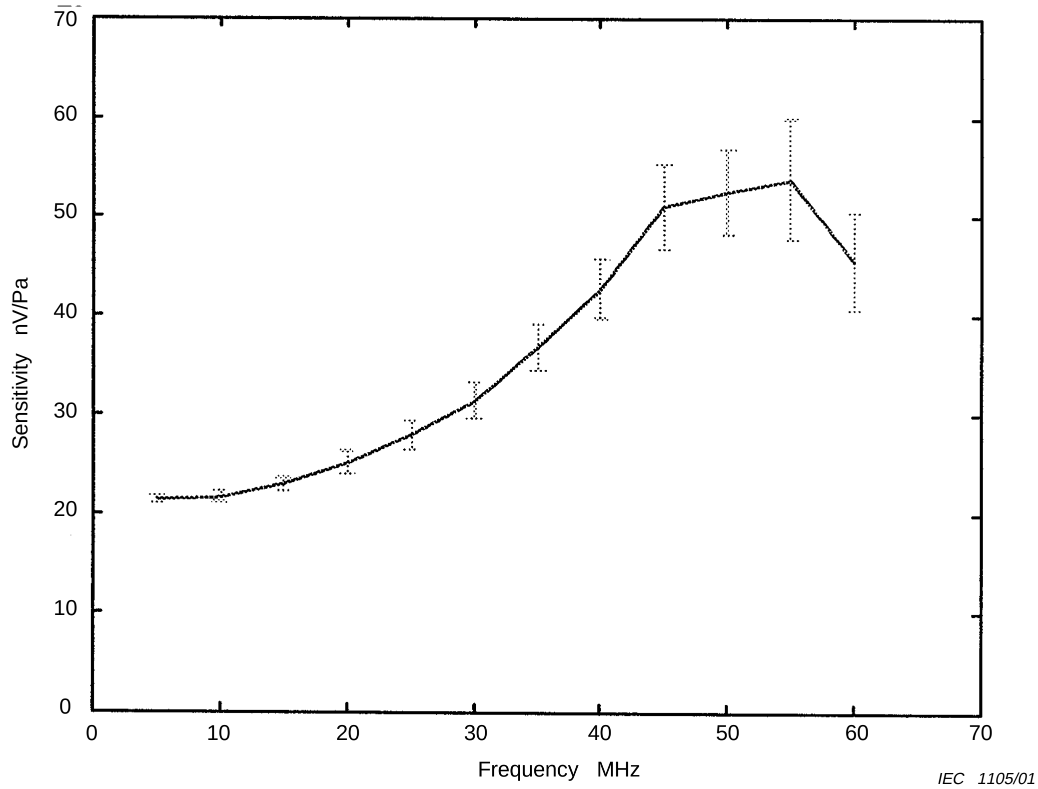


Figure E.5 – Sensitivity of a 0,2 mm active element 9 μm bilaminar membrane hydrophone determined at 5 MHz intervals over the frequency range 5 MHz to 60 MHz

E.3.2.3 Calibrations

Figure E.3 gives the displacement waveform generated by the pellicle positioned at the focus, 51 mm from the focused 5 MHz transducer. Note the absence of any clear distortion of the waveform; this is confirmed by calculating the fourier transform, shown in figure E.4, the lower of the two curves. Differentiating the displacement spectrum yields the pressure spectrum and this is also shown in figure E.4, where frequency components up to 60 MHz may now be readily seen. By comparing the output of the **hydrophone** placed at the same position in the field with the differentiated pellicle spectrum, the **hydrophone** may be calibrated over the frequency range of interest. Figure E.5 shows the calibration results derived for a 9 µm bilaminar membrane **hydrophone** of active element diameter 0,2 mm. The device has a theoretical resonance in its frequency response at 55 MHz which can clearly be seen in the calibration results. The **uncertainties** given on the plot are random **uncertainties** and degrade above about 40 MHz due to the diminished signal-to-noise ratio of the pellicle signal content at these elevated frequencies.

E.3.2.4 Calibration corrections and sources of measurement uncertainty.

Within this subclause, the most significant sources of measurement **uncertainty** associated with the calibration will be briefly outlined.

E.3.2.4.1 Interferometer frequency response

The frequency response of the interferometer is essentially that of the avalanche photodiodes and amplifier. This has been measured in the range 1 kHz to 20 MHz in the past using a frequency response calibrator developed specifically for the purpose [50]. Extension of the working frequency range of the interferometer up to 60 MHz required modifications to be made to the frequency calibrator. Using the modified frequency calibrator, the frequency response of the interferometer was determined up to 100 MHz. **Uncertainties** in the frequency response calibration varied from ±3,5 % (20 MHz) to ±4,3 % (40 MHz).

E.3.2.4.2 Pellicle transmission coefficient

The calibration results must be corrected for the transmission properties of pellicles. Two approaches to deriving this correction are possible, one theoretical and the other experimental. By the use of simple acoustic theory for propagation of plane-waves through layers of dissimilar material, a model was developed to calculate the frequency dependent transmission coefficient of the pellicles. This assumes that attenuation of the acoustic beam in the 25 nm thick gold layer is negligible. Further, an experimental method of determining the transmission coefficient over the range from 2 MHz to 60 MHz was devised, based on a substitution method using a non-linearly distorted field generated by a 2 MHz fundamental transducer. The pellicle was positioned between the transducer and a **hydrophone** (with the pellicle being placed very close to the **hydrophone**), and the transmission coefficient of the pellicle determined. Through a combination of theory and measurement, a frequency dependent correction was applied whose **uncertainty** varied from ±1 % at 5 MHz to ±2 % at 40 MHz.

E.3.2.4.3 Spatial-averaging correction

The narrow beam-widths of the harmonics generated by the 5 MHz focused transducers make it necessary to correct for the spatial-averaging of the pressure distribution over the active element of the **hydrophone**. An experimental investigation of spatial-averaging was undertaken by carrying out beam plots at the focus of the transducer, using the 0,2 mm active element bilaminar **hydrophone**, fourier transforms of the waveforms being carried out so that the harmonic beamwidths could be derived. It is assumed that no spatial-averaging corrections are required for the laser spot, which is 0,1 mm in diameter. **Uncertainties** in the spatial-averaging corrections derived using this assessment varied from ±1 % at 5 MHz to ±6 % at 40 MHz.

E.3.2.4.4 Acousto-optic interaction

Since the optical beam traverses the acoustic beam in the experimental arrangement used, the opportunity exists for the two beams to interact. This means that the displacement measured by the interferometer is not the true displacement of the pellicle membrane, since the optical path length will change due to both the pellicle movement and due to the variation in refractive index along the path of the laser beam. To account for the effect, a relatively large correction must be applied to the measured displacement, which is mainly accomplished by an effective refractive index for water. The accuracy of the correction has been validated for the linear plane-wave regime used for low frequency calibrations [48], but the high amplitude non-linear focused fields used in this work lead to an increase in the **uncertainty** from this source. The acousto-optic effect is the subject of a continuing assessment but work completed to date indicates the **uncertainty** contribution made by the variation in refractive index is no more than ±1 % over the frequency range of interest. The non-plane wave contribution to the effect is estimated to vary from ±0,5% at 5 MHz to ±3 % at 40 MHz.

E.3.2.5 Overall measurement uncertainty

An assessment of the **uncertainty** of the interferometer method of high frequency calibration has been published [51] with estimates of the expanded measurement **uncertainties** varying from ±7 % at 20 MHz to ±11 % at 40 MHz.

E.4 Other methods

E.4.1 Reciprocity

The two-transducer reciprocity calibration method [8, 31] was established in IEC 60866 as the standard calibration method in the frequency range up to 15 MHz. It operates at discrete frequencies. The method has been extended to higher frequencies and has been improved by including the TDS technique in order to obtain a quasi-continuous frequency dependence. Refer to annex D; see also the table of **uncertainties**, table A.1.

E.4.2 Planar scanning

The planar scanning method according to IEC 61101 (up to 15 MHz) is based on the knowledge of the total output power of an ultrasonic source transducer which either is a transferable power standard or can be characterized using a radiation force balance ([52-55], IEC 61161). Power standards have been used up to 21 MHz, but the usefulness of the whole planar scanning calibration method in the frequency range of this International Standard is still uncertain. The overall **uncertainty** of the radiation force measurement is critically dependent on the existence of absorbing targets of high quality, and increases significantly with increasing frequency. To determine the **hydrophone** sensitivity as a function of frequency the field distribution must be known. This requires scanning and will increase the overall **uncertainty**.

E.4.3 Calibration using non-linear KZK wave modelling

This method which has been described in the literature [56, 57] can be understood as semi-primary, as it requires a **hydrophone** calibrated at a single fundamental frequency of the source used to produce the non-linear field.

E.5 General remark

A number of **hydrophone** calibration methods in the frequency range of this International Standard have been listed. Each of the various methods has been described in the literature, but in almost all cases the calibration set-up is unique and involves well-advanced and sophisticated instrumentation, and the practical experience with the particular method is restricted to one laboratory. For this reason, this International Standard refrains from universally defining particular standard calibration methods here. There is, however, general consensus that the methods covered by the table of **uncertainties**, table A.1, can at present be recommended for the calibration of **hydrophones** over the full frequency range of this International Standard. This does not preclude the use of all the other calibration methods described here, provided a full **uncertainty** budget can be given and the general rules of laboratory quality assurance and traceability are observed.

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NOTE γ is referred to as α in Ref. [15]

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- product research ❑
- product design/development ❑
- specifications ❑
- tenders ❑
- quality assessment ❑
- certification ❑
- technical documentation ❑
- thesis ❑
- manufacturing ❑
- other...

Q5 This standard meets my needs: *(tick one)*

- not at all ❑
- nearly ❑
- fairly well ❑
- exactly ❑

Q6 If you ticked NOT AT ALL in Question 5 the reason is: *(tick all that apply)*

- standard is out of date ❑
- standard is incomplete ❑
- standard is too academic ❑
- standard is too superficial ❑
- title is misleading ❑
- I made the wrong choice ❑
- other ....

Q7 Please assess the standard in the following categories, using the numbers:
(1) unacceptable,
(2) below average,
(3) average,
(4) above average,
(5) exceptional,
(6) not applicable

- timeliness ....
- quality of writing....................................
- technical contents...................................
- logic of arrangement of contents ....
- tables, charts, graphs, figures...............
- other ....

Q8 I read/use the: *(tick one)*

- French text only ❑
- English text only ❑
- both English and French texts ❑

Q9 Please share any comment on any aspect of the IEC that you would like us to know:

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