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REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Ultrasonics – Hydrophones –
Part 3: Properties of hydrophones for ultrasonic fields ~~up to 40 MHz~~

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ULTRASONICS – HYDROPHONES –

Part 3: Properties of hydrophones for ultrasonic fields ~~up to 40 MHz~~

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 62127-3:2007+AMD1:2013 CSV. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 62127-3 has been prepared by IEC technical committee 87: Ultrasonics. It is an International Standard.

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

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

a) The upper frequency limit of 40 MHz has been removed.
b) Hydrophone sensitivity definitions have been changed to recognize sensitivities as complex-valued quantities.
c) Procedures to determine the effective hydrophone size have been changed according to the rationale outlined in Annex B.
d) Requirements on the frequencies for which the effective hydrophone size shall be provided have been changed to achieve practicality for increased frequency bands.
e) The new Annex B and Annex C have been added.
f) Annex A has been updated to reflect the changes of the normative parts.

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

Draft	Report on voting
87/818/FDIS	87/824/RVD

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

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

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

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

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

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

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

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INTRODUCTION

The spatial and temporal distribution of acoustic pressure in an ultrasonic field in a liquid medium is commonly determined using miniature ultrasonic **hydrophones**. The properties of these **hydrophones** have been dealt with in a number of IEC standards in various aspects. The purpose of this document is to bring together all these specifications and to establish a common standard on the properties of ultrasonic **hydrophones**. The main **hydrophone** application in this context is the measurement of ultrasonic fields emitted by medical diagnostic equipment in water. Other medical applications are field measurements for therapy equipment such as that used in lithotripsy, high-intensity focused ultrasound (HIFU) and physiotherapy. **Hydrophones** are also used extensively in non-medical applications for both product development and quality control including:

– mapping of the ultrasound field within ultrasonic cleaning baths;

– characterization of acoustic fields used in transmission measurement systems (e.g. ultrasonic spectrometers, ultrasonic attenuation meters and velocimeters);

– characterization of acoustic fields used in reflection measurement systems (e.g. Doppler flowmeters).

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

Underwater **hydrophones** as covered by IEC 60500, IEC 60565-1, and IEC 60565-2 are not included in this document, although there is an overlap in the frequency ranges. Underwater **hydrophones** are used in natural waters, even in the ocean, and this leads to different technical concepts and requirements. In addition, the main direction of acoustic incidence in underwater applications is ~~typically~~ at various angles and often at right angles to the **hydrophone axis**, whereas in this document it is assumed that the main direction of acoustic incidence is in the direction of the **hydrophone axis**.

~~In the past, ultrasonic **hydrophones** have been applied almost exclusively as amplitude sensors. At present a change can be seen and it is increasingly considered useful to have additional phase information, which, however, is only possible if the phase characteristics of the **hydrophone** have been determined during calibration. In this standard, therefore, requirements are specified for the amplitude aspect of the **hydrophone** sensitivity, and recommendations are provided for the phase aspect, as an option to be considered.~~

Historically, ultrasonic **hydrophones** were used almost exclusively as amplitude sensors. However, the complex-valued nature of a **hydrophone's** system response function is well understood and IEC 62127-1:2022 makes use of this within the deconvolution procedures it contains. In this document, requirements are specified for the amplitude aspect of the **hydrophone** sensitivity and recommendations are provided for the phase aspect which can be derived either via calibration, or via calculation methods that are discussed in IEC 62127-1:2022.

ULTRASONICS – HYDROPHONES –

Part 3: Properties of hydrophones for ultrasonic fields ~~up to 40 MHz~~

1 Scope

This part of IEC 62127 specifies relevant **hydrophone** characteristics.

This document 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;
– **hydrophones** with or without an associated pre-amplifier.

2 Normative references

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

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

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

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in IEC 62127-1, IEC 62127-2 and the following apply.

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

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

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

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

[SOURCE: IEC 62127-1:2022, 3.1]

3.2
directional response
description~~, generally presented graphically,~~ of the response of a **hydrophone**, as a function of direction of propagation of the incident plane sound wave, in a specified plane through the **reference centre** and at a specified frequency

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

[SOURCE: IEC 60565:2006, 3.5, modified – In the definition, ", generally presented graphically," has been deleted; "electro-acoustic transducer" has been replaced by "hydrophone"; and "radiated or incident sound" has been replaced by "incident plane sound wave,".]

3.3
effective hydrophone ~~radius~~ size
~~a_h, a_{h3}, a_{h6}~~
a_{h}
~~radius of a stiff disc~~ size of a theoretical receiver **hydrophone** that has a predicted **directional response** function with an angular width equal to the observed angular width

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

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

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

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

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

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

3.4
electric load impedance
$\underline{Z}_{\mathrm{L}}$
complex electric input impedance (consisting of a real and an imaginary part) to which the **hydrophone** ~~or **hydrophone assembly**~~ unit output cable is connected or is intended to be connected

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

[SOURCE: IEC 62127-1:2022, 3.22]

~~**3.4**~~
~~**end-of-cable**~~
~~specification that relates to the end of the integral output cable if the **hydrophone** or **hydrophone assembly** is provided with such a cable; if the **hydrophone** or **hydrophone assembly** is not provided with an integral output cable, the specification relates to the output connector firmly connected with the **hydrophone** or **hydrophone assembly**, not to an extra cable~~

3.5
end-of-cable
<**hydrophone** or **hydrophone assembly** with integral output cable> relating to the end of the integral output cable

3.6
end-of-cable
<**hydrophone** or **hydrophone assembly** without integral output cable> relating to the output connector firmly connected with the **hydrophone** or **hydrophone assembly** and not to an extra cable

3.7
end-of-cable loaded sensitivity
~~**end-of-cable loaded sensitivity** of a **hydrophone** or **hydrophone assembly**~~
~~***M*L**~~
~~ratio of the instantaneous voltage at the end of any integral cable or output connector of a **hydrophone** or **hydrophone assembly**, when connected to a specified **electric load impedance**, to the instantaneous acoustic pressure in the undisturbed **free field** of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed~~

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

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

$$\underline{M}_{\mathrm{L}}(f) = \frac{\mathcal{F}\left(u_{\mathrm{L}}(t)\right)}{\mathcal{F}\left(p(t)\right)} \tag{1}$$

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

3.8
end-of-cable open-circuit sensitivity
~~**end-of-cable open-circuit sensitivity of a hydrophone**~~
~~***M*c**~~
~~ratio of the instantaneous, open-circuit voltage at the end of any integral cable or output connector of a **hydrophone** to the instantaneous acoustic pressure in the undisturbed **free field** of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed~~

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

~~NOTE 2 This corresponds to the **free field** sensitivity as defined in IEC 60565:2006, 3.15.~~

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

$$\underline{M}_{\mathrm{c}}(f) = \frac{\mathcal{F}\left(u_{\mathrm{c}}(t)\right)}{\mathcal{F}\left(p(t)\right)} \tag{2}$$

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

3.9
end-of-cable loaded sensitivity level
$L_{M_\mathrm{L}}(f)$
<of a **hydrophone** or **hydrophone assembly**> twenty times the logarithm to the base 10 of the quotient of the modulus of the **end-of-cable loaded sensitivity** $|\underline{M}_\mathrm{L}(f)|$ to a reference sensitivity M_ref

$$L_{M_\mathrm{L}}(f) = 20\log_{10}\frac{|\underline{M}_\mathrm{L}(f)|}{M_\mathrm{ref}}\ \mathrm{dB} \qquad (3)$$

Note 1 to entry: Commonly used values of the reference sensitivity M_ref are 1 V/μPa or 1 V/Pa.

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

3.10
free field
sound field in a homogeneous and isotropic medium in which the effects of boundaries are negligible

[SOURCE: IEC 60565:2006, 3.13]

3.11
hydrophone geometrical ~~radius~~ size
geometrical ~~radius~~ size of a hydrophone active element
a_g
~~radius~~ size defined by the ~~dimensions~~ lateral extents of the active element of a **hydrophone**

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

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

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

3.12
hydrophone
transducer that produces electric signals in response to ~~waterborne acoustic signals~~ pressure fluctuations in water

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

3.13
hydrophone assembly
combination of **hydrophone** and **hydrophone pre-amplifier**

3.14
hydrophone axis
nominal symmetry axis of the **hydrophone** active element

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

3.15
hydrophone pre-amplifier
active electronic device connected to, or to be connected to, a particular **hydrophone** and reducing its output impedance

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

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

3.16
reference centre
point on or near a **hydrophone** about which its acoustic receiving sensitivity is defined

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

[SOURCE: IEC 60565:2006, 3.25, modified – In the definition, "transducer" has been replaced by "hydrophone" and "transmitting responses" has been omitted. The note has been replaced.]

3.17
uncertainty
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

Note 1 to entry: See ISO/IEC Guide 98-3:2008 [2], 2.2.3.

[SOURCE: IEC 62127-1:2022, 3.92]

4 List of symbols

a_g	**hydrophone geometrical** ~~radius~~ **size**
a_h	**effective hydrophone** ~~radius~~ **size** ~~(a_{h3}, a_{h6}: with special reference to a 3 dB or 6 dB definition, respectively)~~
c	speed of sound in a medium
D_H	model function used during the determination of **effective hydrophone size** from a measured **directional response** of a **hydrophone**
f	frequency
k	wavenumber, equal to $2\pi/\lambda$
$L_{M_L}(f)$	**end-of-cable loaded sensitivity level**
$\underline{M}$	general symbol for the complex **hydrophone** sensitivity, $M = \lvert\underline{M}\rvert$ being its modulus and arg($\underline{M}$) being its argument (equal to phase angle)
~~M_c~~ $\underline{M}_c$	end-of-cable open-circuit sensitivity
~~M_L~~ $\underline{M}_L$	end-of-cable loaded sensitivity
$\underline{Z}_h$	complex electric output impedance of a **hydrophone** or **hydrophone assembly**
$\underline{Z}_L$	**electric load impedance**
θ	angle of incidence of an ultrasonic wave with respect to the **hydrophone axis** ~~(θ_3, θ_6: with special reference to 3 dB and 6 dB defined levels)~~

5 Hydrophone characteristics

5.1 General

For a full characterization of the hydrophone performance in the frequency range of this document, the following information is required. Examples of information on hydrophone characteristics are provided in Annex A.

NOTE Determination methods are covered in IEC 62127-2.

5.2 Basic information

The following shall be briefly stated:

– the basic physical principles of the transduction process, the type of sensor material involved, the form and geometrical dimensions (diameter, thickness) of the **hydrophone** active element and the needle diameter in case of a needle **hydrophone**;
– the configuration and design of the **hydrophone**;
– whether or not a pre-amplifier is associated with the **hydrophone**; if the pre-amplifier can be disconnected from the **hydrophone**, clear information shall be given as to which pre-amplifier type belongs to which **hydrophone** type;
– the nominal direction of ultrasonic incidence in relation to the **hydrophone**.

NOTE The last point is important, as it has been found in the literature [3][1] that even with membrane **hydrophones**, the response ~~might~~ can change upon reversal of the ultrasonic propagation direction in relation to the **hydrophone**.

The following should be briefly stated:

– the lateral and thickness dimensions of the **hydrophone** active element;
– the frequency of the fundamental thickness resonance of the **hydrophone** active element;
– the size and ~~weight~~ mass of the **hydrophone**;
– the recommended **directional response** model (see 5.6.2) appropriate for the **hydrophone**;
– in the case of a membrane **hydrophone**, the acoustic reflection and transmission factor (preferably as a function of frequency);
– information on preamplifier roll-off at low frequencies outside the hydrophone calibration range, if applicable, to support appropriate calibration data extrapolation in accordance with IEC 62127-1:2022.

General note relating to 5.3 and 5.4: if phase information is available, the phase angle (which equals the argument of the complex **hydrophone** sensitivity) should be stated in addition to the sensitivity (which equals the modulus of the complex **hydrophone** sensitivity), as well as the frequency dependence of the phase angle in addition to the frequency dependence of the sensitivity.

5.3 Sensitivity

The modulus of the **end-of-cable** sensitivity of the **hydrophone** or **hydrophone assembly** shall be stated in units of volt per pascal (V/Pa) or in decimal submultiples, or as a logarithmic level in decibels (dB) with reference to a stated sensitivity value.

NOTE 1 Refer to 3.9 regarding the definition of the **end-of-cable loaded sensitivity level**.

If a pre-amplifier contributes to the sensitivity value given, this shall be stated.

It shall be stated whether the sensitivity value given is understood as the **end-of-cable open-circuit sensitivity** or as the **end-of-cable loaded sensitivity**. In the latter case, the relevant

[1] Numbers in square brackets refer to the Bibliography.

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.

The frequency interval over which the sensitivity is given and over which the **uncertainty** applies shall be stated. For the purposes of this document, sensitivity and **uncertainty** values may be given separately for several frequency intervals.

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

The temperature dependence of the sensitivity shall be given. The **hydrophone** sensitivity shall be stated as a function of the water temperature, at least over the temperature range 19 °C to 25 °C, or the particular water temperature to which the stated sensitivity relates shall be stated together with the temperature coefficient of the sensitivity.

A recommended calibration period shall be provided in the instructions for use. This recommendation ~~shall be followed,~~ applies unless otherwise stated by specific device application standards.

NOTE 2 A calibration period of one year will be appropriate in most cases.

The **reference centre** shall be stated if the sensitivity does not relate to the geometrical centre of the front surface of the **hydrophone** active element.

NOTE 3 This is particularly important for any phase considerations.

The direction of acoustic incidence shall be stated if the sensitivity does not relate to an incidence in the direction of the **hydrophone axis**.

5.4 Frequency response

5.4.1 Stated frequency band

The frequency band claimed for the **hydrophone** or **hydrophone assembly** shall be stated by giving the lower frequency limit and the upper frequency limit. The modulus of the **end-of-cable** sensitivity of the **hydrophone** or **hydrophone assembly** shall be constant over the stated frequency band with a tolerance which shall also be stated.

5.4.2 Frequency dependence

The modulus of the **end-of-cable** sensitivity or sensitivity level of the **hydrophone** or **hydrophone assembly** 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 5.4.1. If it is given as a list of values or as discrete points in a graph, the frequency distance between adjacent points should be low enough so that all important details of the frequency dependence are shown and the sensitivity level does not vary by more than ±1 dB between adjacent points.

The frequency response may be given in terms of absolute sensitivity values or in a relative representation, relative with reference to the absolute sensitivity of the **hydrophone** or **hydrophone assembly** 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 phase of the **end-of-cable** sensitivity may be given as a function of frequency either graphically or as a list of values.

The statement of the frequency response shall refer to the same conditions (i.e. loaded or open-circuit output of the **hydrophone** or **hydrophone assembly**) as the sensitivity statement in accordance with 5.3.

If the **uncertainty** of the sensitivity values in the frequency response representation differs from the ~~general~~ **uncertainty** assessment of 5.3, this shall be clearly stated and the new or additional **uncertainty** shall be given. ~~If the frequency response is presented graphically only, the additional **uncertainty** due to reading 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 (**end-of-cable**, loaded or open-circuit), the sensitivity statement in accordance with 5.3 may be omitted.

NOTE 1 The frequency response ~~might~~ can depend on the electric load conditions.

NOTE 2 If, in a practical application, the **hydrophone** or **hydrophone assembly** is used with subsequent electronic components such as an amplifier, oscilloscope, etc., the frequency response of the whole system will also be, of course, influenced by the frequency response of these additional components.

5.5 Directional response

5.5.1 General

Directional response, and quantities derived from it, are subject to numerous changes relative to the first edition of IEC 62127-3. Details for the rationale behind these changes can be found in Annex B.

5.5.2 Determination of the directional response

~~The **directional response** of the **hydrophone** shall be stated at both the lower and upper limits of the frequency band claimed under 5.4.1. The determination method used shall also be stated. The **directional response** shall also be stated at a frequency which agrees within ± 15 % with the geometric mean of the lower and upper frequency limits, and at a frequency close to the fundamental thickness resonance if this resonance is inside the claimed frequency band.~~

The **directional response** of the **hydrophone** shall be stated at a minimum of three frequencies where the lowest and highest frequencies are as widely separated as possible.

– The lowest frequency at which the **directional response** of the **hydrophone** has been determined should be the lower limit of the frequency band claimed under 5.4.1. If not, the reason(s) for variation shall be stated.

– The highest frequency at which the **directional response** of the **hydrophone** has been determined should be the upper limit of the frequency band claimed under 5.4.1. If not, the reason(s) for variation shall be stated.

  NOTE Experimental determination of **directional response** becomes increasingly challenging as frequency increases. Consequently, the highest frequency at which it is practical to determine the **directional response** of the **hydrophone** can be lower than the upper frequency band claimed under 5.4.1. However, **effective hydrophone size** becomes asymptotic as frequency increases. Therefore, it is likely that there is negligible variation in **effective hydrophone size** at frequencies above the highest frequency at which **directional response** has been evaluated.

– The midpoint frequency that is within ±15 % of the geometric mean of the lowest and highest frequencies at which **directional response** of the **hydrophone** has been determined is the third frequency at which the directional response shall be stated. If not, the reason(s) for variation shall be stated.

– If the **hydrophone** has a fundamental thickness resonance within range of the lowest and highest frequencies in this subclause 5.5.2, the **directional response** at this frequency shall also be stated. If not, the reason(s) for variation shall be stated.

The **directional response** should be measured by rotating the **hydrophone** about an axis, which passes through the **reference centre** and 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 ~~greater~~ smaller. If this method is used, 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. If the active element is non-circular, one of the rotational axes shall be in the direction of the largest dimension. The directions of the rotational axes shall be identified on the **hydrophone** using a mark or in the accompanying literature.

The angular increment shall be chosen to ensure that the variation between adjacent points in the **directional response** is not more than 1 dB.

The measurement of the **directional response** shall be carried out in ~~an almost plane~~ a quasi-planar wave ultrasonic field.

If the active element is irregular in shape, or has more than two symmetry axes, the **directional response** should be measured around additional axes.

Each of the resulting **directional responses** obtained from the measurements shall be stated.

5.5.3 Symmetry of directional response

If, in any of the **directional response** results obtained, the angle between the direction of maximum response and the **hydrophone axis** is greater than one tenth 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 shall be given. The sensitivity level in the direction of the **hydrophone axis** shall be not lower than the maximum in any other direction minus 2 dB.

The symmetry of any **directional response** should be such that if a normalized sensitivity level of −6 dB occurs for some particular direction subtending a certain angle to the direction of maximum sensitivity (0 dB), then the sensitivity level measured on the opposite side subtending the same angle to the direction of maximum sensitivity shall be ~~within the range~~ −6 dB ± 3 dB.

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

~~5.6 Effective radius~~

~~From the **directional response** results obtained in accordance with 5.5, a value for the **effective radius** of the **hydrophone** active element shall be derived and stated as follows, and again at the frequencies given in 5.4.1~~

~~If, in the **directional response** considered, the angular difference between the left-hand −3 dB direction and the right-hand −3 dB direction is~~ $\cancel{2\theta_3}$ ~~and the angular difference between the left-hand −6 dB direction and the right-hand −6 dB direction is~~ $\cancel{2\theta_6}$~~, the following formulas for the **effective radii** shall apply under the assumption of circular geometry:~~

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

~~and~~

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

~~where~~

~~*f* is the relevant ultrasonic frequency of the particular measurement; and~~

~~*c* is the speed of sound in the liquid medium at the particular temperature.~~

~~The resulting **effective radius** associated with the **directional response** considered shall be calculated as the average of a_{h3} and a_{h6}.~~

~~If the active element is circular, the **effective radius** of the **hydrophone** shall be given as the average of the two **effective radii** obtained at the two orthogonal rotational axes. If the active element is non-circular, the highest of the **effective radii** obtained from the various **directional responses** shall be given as the **effective radius** of the **hydrophone**. If, in the latter case, the theoretical relation between the **directional response** and the **effective radius** is known for that particular shape, this formula shall be used; otherwise equation (1) and equation (2) shall be used as an approximation.~~

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

5.6 Effective hydrophone size

5.6.1 General

From the **directional response** results obtained in accordance with 5.5, a value for the **effective hydrophone size** shall be derived and stated as follows.

5.6.2 Model of directional response

When determining the **effective hydrophone size**, the theoretical model against which the experimentally determined **directional response** is being compared shall be stated. To maintain consistency with the first edition of IEC 62127-3, the default model shall be the rigid baffle piston model [see a)1) below] unless clear justification is provided for the choice of an alternative model of directional response. Possible alternative models are given in a)2) to a)5) and in b).

a) For nominally circular shaped **hydrophone** active elements, appropriate models of **directional response** are:

1) rigid baffle piston model

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1[ka\sin(\theta)]}{ka\sin(\theta)} \tag{4}$$

2) soft baffle piston model [4]

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1[ka\sin(\theta)]}{ka\sin(\theta)}\cos(\theta) \tag{5}$$

3) unbaffled piston model

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1[ka\sin(\theta)]}{ka\sin(\theta)}\cdot\frac{1+\cos(\theta)}{2} \tag{6}$$

4) rigid piston model (for probe, needle and fibre-optic hydrophones) [5]

$$D_H(k,a,\theta) = \frac{2J_1[ka\sin(\theta)]}{ka\sin(\theta)} + \frac{ik\cos(\theta)}{\pi a^2}\int_A\int_B \frac{e^{-ikx\sin(\theta)}e^{iks}}{2\pi s}\mathrm{d}A\,\mathrm{d}B \tag{7}$$

where A and B are areas of integration representing the area of the **hydrophone** active element and the end of the probe upon which the **hydrophone** active element is mounted, and s is the distance between the point of observation and the point of integration;

5) Bacon model (for membrane hydrophones including Lamb waves) [6]

$$D_H(k,a,\theta_1) = \frac{2J_1[k_1a\sin(\theta_1)]}{k_1a\sin(\theta_1)}\cdot\frac{\cos(\theta_1)}{\delta}\cdot\left|\left\{\frac{\cos 2\gamma_2}{\cos^2\theta_2}\left(\delta-\eta\sin^2\gamma_2\right)\right\}\right|\cdot\frac{|g(M,N)|}{|g(M_0,N_0)|} \tag{8}$$

Further information concerning the terms of this formula is provided in Annex C.

b) For nominally rectangular shaped hydrophone active elements,

$$D_H(k,L,\theta) = \frac{\sin\left[\dfrac{kL\sin(\theta)}{2}\right]}{\dfrac{kL\sin(\theta)}{2}} \tag{9}$$

where L is the length of one of the sides of the rectangle.

If the model relies upon one or more properties of the materials involved (for example the Bacon model), the values used for these properties shall be stated.

5.6.3 Fitting of experimental response to theoretical predictions

The **directional response** is expected to exhibit a clear central lobe (possibly with other features such as localized minima to either side of the lobe, or off-axis peaks) and the angular range used for fitting shall be restricted to that which contains the main lobe only and is defined by $\theta_{min} < \theta < \theta_{max}$.

Given a centre position of θ = 0°, θ_{limit} is the minimum of:

- the modulus of the first angle at which the **directional response** curve drops 6 dB below the value of the **directional response** at θ = 0°, or
- 35°.

θ_{min} is defined as $-\theta_{limit}$ in the angular range θ < 0°, and

θ_{max} is defined as θ_{limit} in the angular range θ > 0°.

The **effective hydrophone size** shall be determined as that value of a which minimizes the sum of the squared residual between the magnitude of the model predictions $|D_H(k,a,\theta)|$ and the magnitude of the experimentally determined values $|x(\theta)|$ of the normalized directional response. This shall be repeated at each frequency given in 5.5.2.

$$S = \sum_{\theta=\theta_{min}}^{\theta_{max}} \left(\left| x(\theta) \right| - \left| D_{H}(k,a,\theta) \right| \right)^2 \quad (10)$$

If the active element is nominally circular, the **effective hydrophone size** shall be given as the average of the two effective radii obtained at the two orthogonal rotational axes.

If the active element is nominally non-circular, the largest of the **effective hydrophone sizes** obtained from the various **directional responses** shall be given as the **effective hydrophone size**.

NOTE The **effective hydrophone size** is usually a function of the frequency. For representative experimental data see Annex A.

5.7 Dynamic range, linearity and electromagnetic interference

The dynamic range of the **hydrophone** or **hydrophone assembly**, i.e. the pressure amplitude range in which the **hydrophone** or **hydrophone assembly** can be used, shall be stated.

This range shall meet at least the following conditions:

a) no mechanical or electrical damage to the **hydrophone** or **hydrophone assembly**;
b) no output saturation;
c) the output signal shall 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 ~~might~~ can depend on electromagnetic interference and ~~might~~ can thus vary with the electromagnetic conditions at the place of measurement. Ideally, it ~~might~~ is be possible to give a noise level representing all other sources of noise except electromagnetic interference.

The linear range of the **hydrophone** or **hydrophone assembly**, i.e. the pressure amplitude range in which the **hydrophone** or **hydrophone assembly** behaves in a linear way according to the condition below, shall be stated.

The condition is as follows. If, on a plot of **end-of-cable** output voltage against **free field** acoustic pressure amplitude, a straight line can be drawn through the origin in such a way that over a certain pressure range the actual voltage values do not deviate from the straight line by more than ±10 %, this range is the linear range of the **hydrophone** or **hydrophone assembly**. This shall be the case for any frequency within the frequency band claimed under 5.4.1.

Information or advice on how to minimize the effects of electromagnetic interference should be provided.

5.8 Electric output characteristics

5.8.1 Hydrophone without pre-amplifier

The **end-of-cable** complex electric output impedance, $\underline{Z}_{h}$, of the **hydrophone** 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 shall be clearly stated (e.g. the resistance being in series or parallel to the capacitance).

The relation between the complex **end-of-cable loaded sensitivity** and the complex **end-of-cable open-circuit sensitivity** will depend on $\underline{Z}_{h}$ and $\underline{Z}_{L}$ and is given by

$$\underline{M}_{\mathrm{L}} = \underline{M}_{\mathrm{c}}\ \{\underline{Z}_{\mathrm{L}}/(\underline{Z}_{\mathrm{h}} + \underline{Z}_{\mathrm{L}})\} \tag{11}$$

with the moduli being given by

$$\cancel{M_{\mathrm{L}} = M_{\mathrm{c}} \left\{ \frac{\mathrm{Re}^2 \underline{Z}_{\mathrm{L}} + \mathrm{Im}^2 \underline{Z}_{\mathrm{L}}}{\left[\mathrm{Re}\underline{Z}_{\mathrm{h}} + \mathrm{Re}\underline{Z}_{\mathrm{L}}\right]^2 + \left[\mathrm{Im}\underline{Z}_{\mathrm{h}} + \mathrm{Im}\underline{Z}_{\mathrm{L}}\right]^2} \right\}^{1/2}}$$

$$\left|\underline{M}_{\mathrm{L}}\right| = \left|\underline{M}_{\mathrm{c}}\right| \left\{ \frac{\mathrm{Re}^2 \underline{Z}_{\mathrm{L}} + \mathrm{Im}^2 \underline{Z}_{\mathrm{L}}}{\left[\mathrm{Re}\underline{Z}_{\mathrm{h}} + \mathrm{Re}\underline{Z}_{\mathrm{L}}\right]^2 + \left[\mathrm{Im}\underline{Z}_{\mathrm{h}} + \mathrm{Im}\underline{Z}_{\mathrm{L}}\right]^2} \right\}^{1/2} \tag{12}$$

where

$\left|\underline{M}_{\mathrm{L}}\right|$ is the modulus of the **end-of-cable loaded sensitivity**;

$\left|\underline{M}_{\mathrm{c}}\right|$ is the modulus of the **end-of-cable open-circuit sensitivity**;

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

Formula (11) and Formula (12) may 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.

NOTE Formula (11) and Formula (12) apply to a frequency domain consideration. In practical **hydrophone** applications with ultrasonic pulses, time domain considerations (temporal convolution and deconvolution) would need to be taken into account.

For a **hydrophone** without a pre-amplifier, the **hydrophone end-of-cable** sensitivity can be stated as either loaded sensitivity or open-circuit sensitivity.

If the **end-of-cable** sensitivity is stated as loaded sensitivity, the relevant electric load conditions (**electric load impedance** or equivalent network components) to which the sensitivity values relate shall be stated. If the **hydrophone** is used under different load conditions, the sensitivity shall be corrected in accordance with Formula (12).

If the **end-of-cable** sensitivity is given as open-circuit sensitivity and if the **hydrophone** output is connected to a finite **electric load impedance**, the sensitivity shall be corrected in accordance with Formula (12).

5.8.2 Hydrophone assembly

For a **hydrophone assembly**, the **end-of-cable** sensitivity shall be stated as loaded sensitivity, and the relevant electric load conditions (**electric load impedance** or equivalent network components) to which the sensitivity values relate shall be stated. If the **hydrophone assembly** is used under different load conditions, the sensitivity needs to be corrected.

5.8.3 Output lead configuration

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

5.9 Environmental aspects

5.9.1 Temperature range

The permitted operating and storage temperature range for the **hydrophone** or **hydrophone assembly** shall be stated by the manufacturer.

5.9.2 Water tightness

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

5.9.3 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 of **hydrophone** properties refer shall be stated.

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

5.9.4 Exposed material

Types of material (metal, rubber, casting resin, etc.) exposed to the liquid in which the **hydrophone** is allowed to be used shall be stated. All exposed **hydrophone** parts shall be made from corrosion-compatible and corrosion-resistant materials. In particular, the use of a variety of metals for exposed components should be avoided to avert the possible occurrence of galvanic corrosion.

Exposed metal parts of the **hydrophone** housing and electrostatic shield shall be connected to the cable screen.

5.10 Guidance manual

A detailed guidance manual shall be provided with the **hydrophone** or **hydrophone assembly**.

In addition to the information specified in 5.2 to 5.9, the manual should include the following:

– a drawing that shows the geometrical shape and size of the **hydrophone** or **hydrophone assembly**;
– guidance on the proper and safe use of the **hydrophone** or **hydrophone assembly**, including soak time, temperature range and maximum ultrasonic pressure;
– typical impedance plot and amplifier gain plot (if applicable) as a function of frequency.

5.11 List of hydrophone characteristics

The required information on **hydrophone** properties is summarized in the following list:

– basic information, such as the acoustically active material, geometrical dimensions (lateral and thickness) of active element and whether or not a pre-amplifier is included;
– **hydrophone** sensitivity;
– frequency response (of the sensitivity) and the fundamental thickness resonance frequency;
– **directional response** and **effective** ~~radius~~ **hydrophone size**;
– dynamic range and linear range;
– electric output impedance and lead configuration;
– environmental aspects.

Annex A
(informative)

Examples of information on hydrophone properties

A.1 General

This Annex A provides sample information on a 0,2 mm needle **hydrophone** that is designed to be used in conjunction with a submersible **hydrophone pre-amplifier**. Wherever acoustic properties of the **hydrophone** are stated, they relate to the **hydrophone/pre-amplifier** combination (**hydrophone assembly**).

NOTE The material given in this Annex A only demonstrates how information is to be presented. It is not an endorsement of a specific product.

A.2 Basic information

Basic information for the example of a 0,2 mm nominal diameter needle hydrophone assembly is provided in Table A.1.

Table A.1 – Example of basic information for 0,2 mm needle hydrophone assembly

Required characteristic information	Example 0,2 mm needle hydrophone
Transduction method	Piezoelectric conversion
Sensor material	Polyvinylidene fluoride (PVDF)
Active element ~~geometrical dimensions~~	Circular element, diameter 0,2 mm, thickness 9 µm
Piezo-film thickness resonance frequency	~~63~~ 53 MHz
Typical sensitivity ~~at 3~~ in the range 5 MHz to 35 MHz	50 nV/Pa (further data in Clause A.3)
Outer diameter of needle shaft	0,5 mm
~~Weight~~ Mass of **hydrophone**	1,5 g
Length of **hydrophone**	Overall: 55 mm, needle shaft: 35 mm
Pre-amplifier	**Hydrophone** to be used in conjunction with a submersible pre-amplifier with generic model number NNNN
Nominal output impedance	50 Ω
Intended orientation in use (nominal direction of ultrasound incidence)	Needle tip pointing directly towards the acoustic source

A.3 Sensitivity and frequency response

~~Figure A.1 shows the **end-of-cable loaded sensitivity** for the needle **hydrophone** used in conjunction with its appropriate pre-amplifier, when loaded by 50 Ω.~~

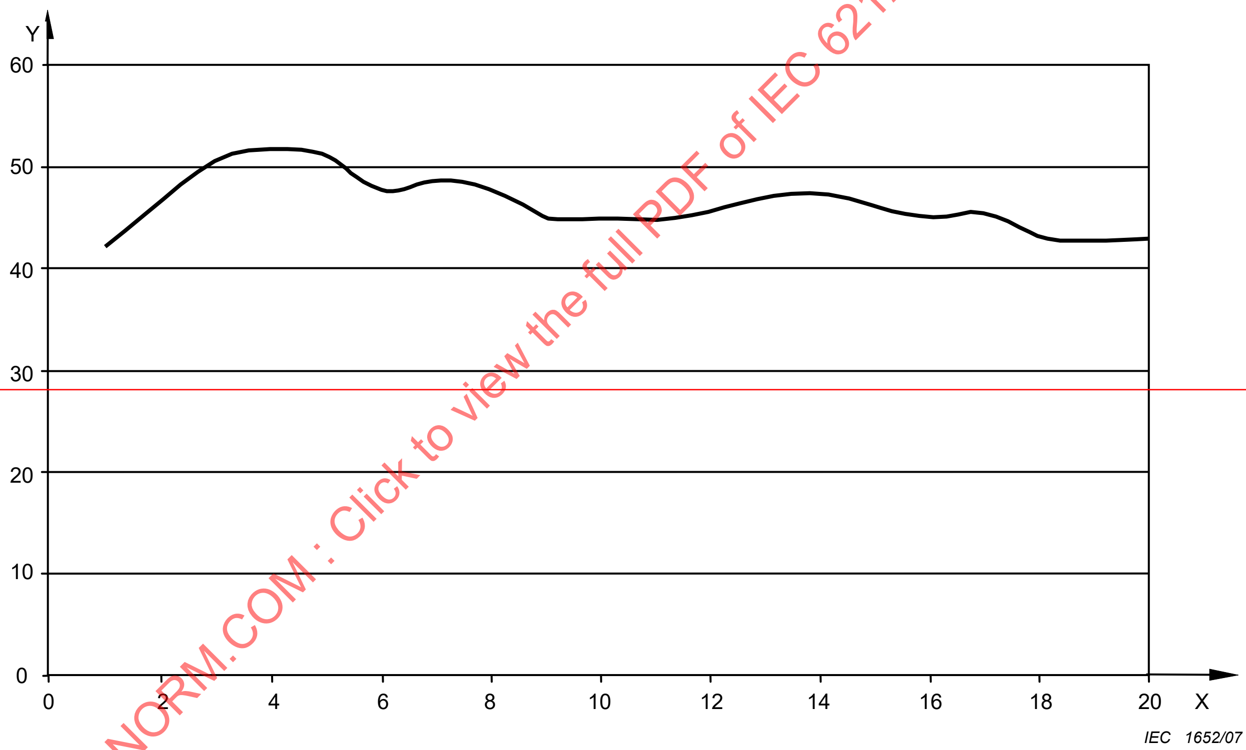
~~This frequency response graph was obtained by substitution calibration and follows the method described by Smith and Bacon [1]. It made use of an ultrasonic source that produced a highly shocked waveform containing a wide harmonic content. This calibration used an acoustic source with a fundamental frequency of 1 MHz. This provided a source waveform with a significant ultrasonic energy signal at integer multiples of the fundamental and thereby permitted calibration of the **hydrophone** from 1 MHz to 20 MHz in 1 MHz increments.~~

This frequency response of the **hydrophone** was obtained by two substitution calibrations; reported responses are the **end-of-cable loaded sensitivity** for the needle **hydrophone** used in conjunction with its appropriate pre-amplifier, when loaded by 50 Ω. For the response in the range 1 MHz to 40 MHz, the procedure follows the method described by Smith and Bacon [7]. This method uses an ultrasonic source that produced a highly shocked waveform containing a wide harmonic content with many components at integer multiples of the fundamental frequency of 1 MHz. This enables a calibration of the **hydrophone** from 1 MHz to 40 MHz in 1 MHz increments. The data are displayed in Figure A.1. Spline interpolation was used to produce the data between the calibrated sensitivities.

Below 1 MHz, frequency response was also determined by substitution calibration, but with a different source. Here a broadband piezo-composite transducer was subject to an impulse excitation signal and spectral information was extracted in the range 100 kHz to 1 MHz in 50 kHz increments. The data are displayed in Figure A.2.

The **hydrophone** was calibrated at (20 ± 2) °C.

NOTE 1 The temperature coefficient of the sensitivity is given in Clause A.8.



~~**Key**~~

~~X frequency (MHz)~~

~~Y sensitivity (nV/Pa)~~

~~**Figure A.1 – Frequency response of 0,2 mm needle hydrophone**~~

~~**Hydrophone** sensitivity: (47 ± 5) nV/Pa~~

~~**Hydrophone** frequency band: 1 MHz to 20 MHz~~

~~Measurement **uncertainty** 1 MHz to 8 MHz: 14 %, 9 MHz to 20 MHz: 18 %~~

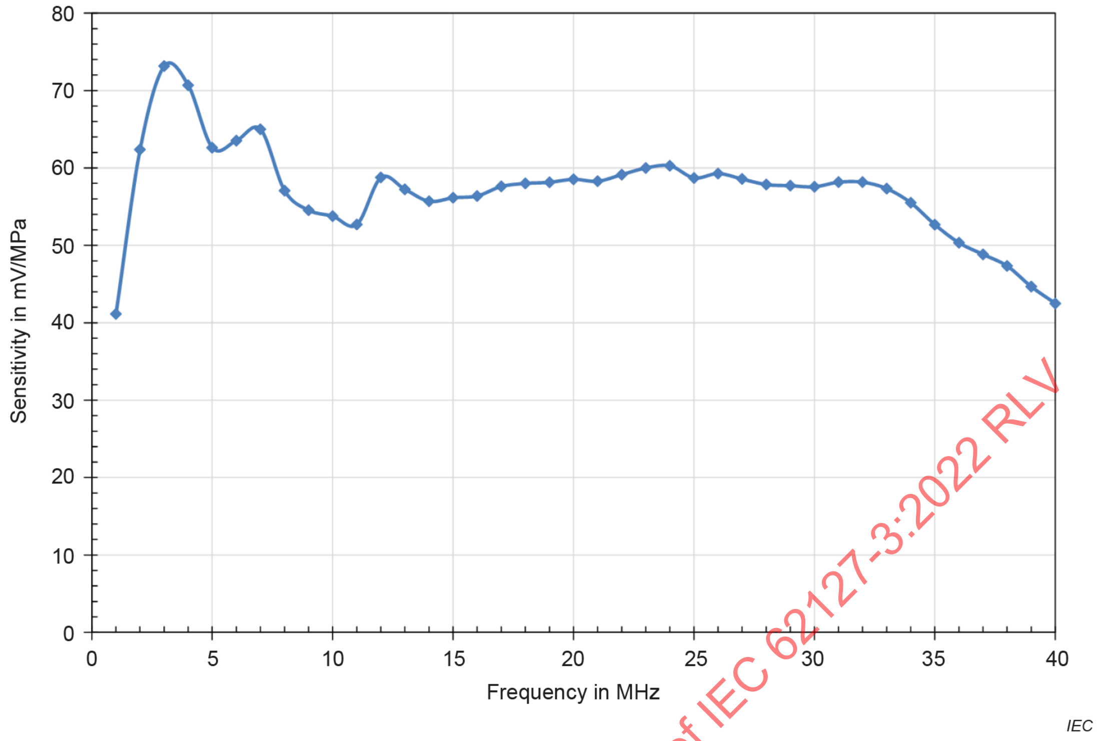


Figure A.1 – Frequency response of 0,2 mm needle hydrophone in the range 1 MHz to 40 MHz

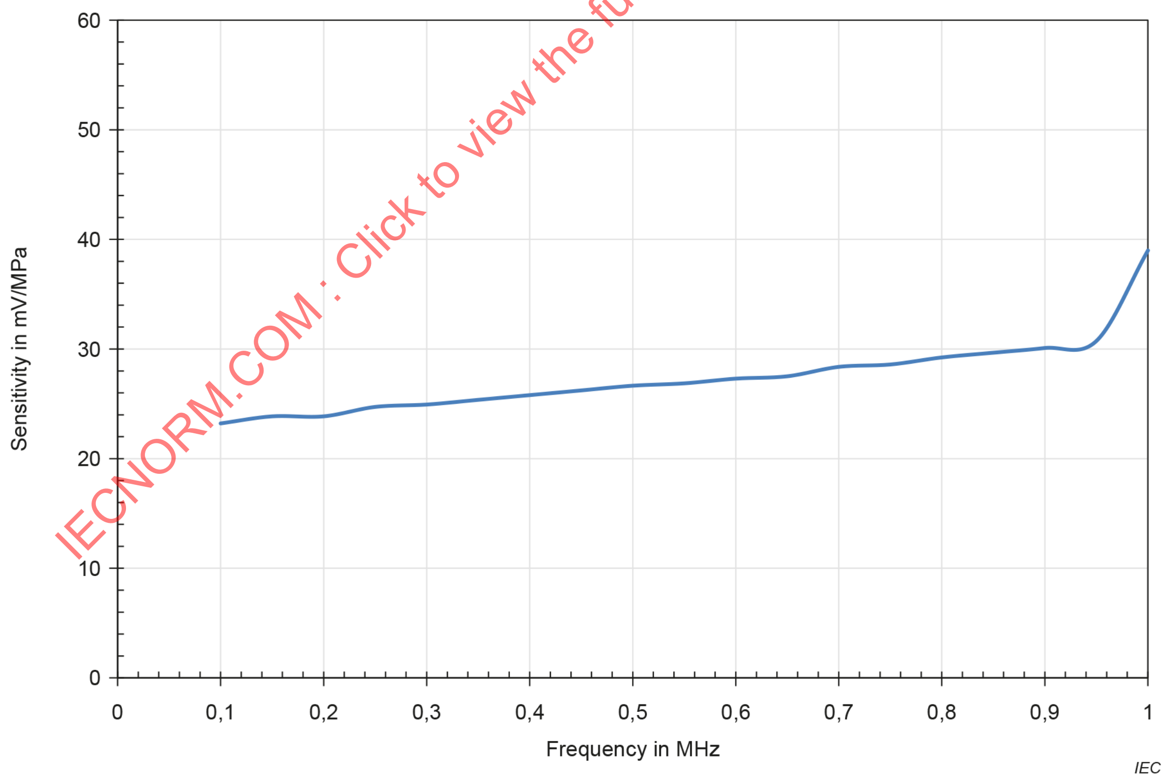


Figure A.2 – Frequency response of 0,2 mm needle hydrophone in the range 100 kHz to 1 MHz

Mean **hydrophone** sensitivity in the range 1 MHz to 40 MHz: 50 mV/MPa

Mean **hydrophone** sensitivity in the range 0,1 MHz to 0,95 MHz: 27 mV/MPa

Sensitivity level variation between individual probes: approximately ±3 dB

Hydrophone frequency band: 0,1 MHz to 40 MHz

Measurement **uncertainty:**

Frequency range	Expanded uncertainty
0,1 MHz to 1 MHz	11 %
1 MHz to 8 MHz	14 %
9 MHz to 20 MHz	17 %
21 MHz to 40 MHz	19 %

The measurement **uncertainty** for the frequency response measurement was determined in accordance with the methods established in [2]. One of the main **uncertainty** contributions is the **uncertainty** due to the calibration of the reference **hydrophone** used in the calibration, which itself is traceable to national primary standards.

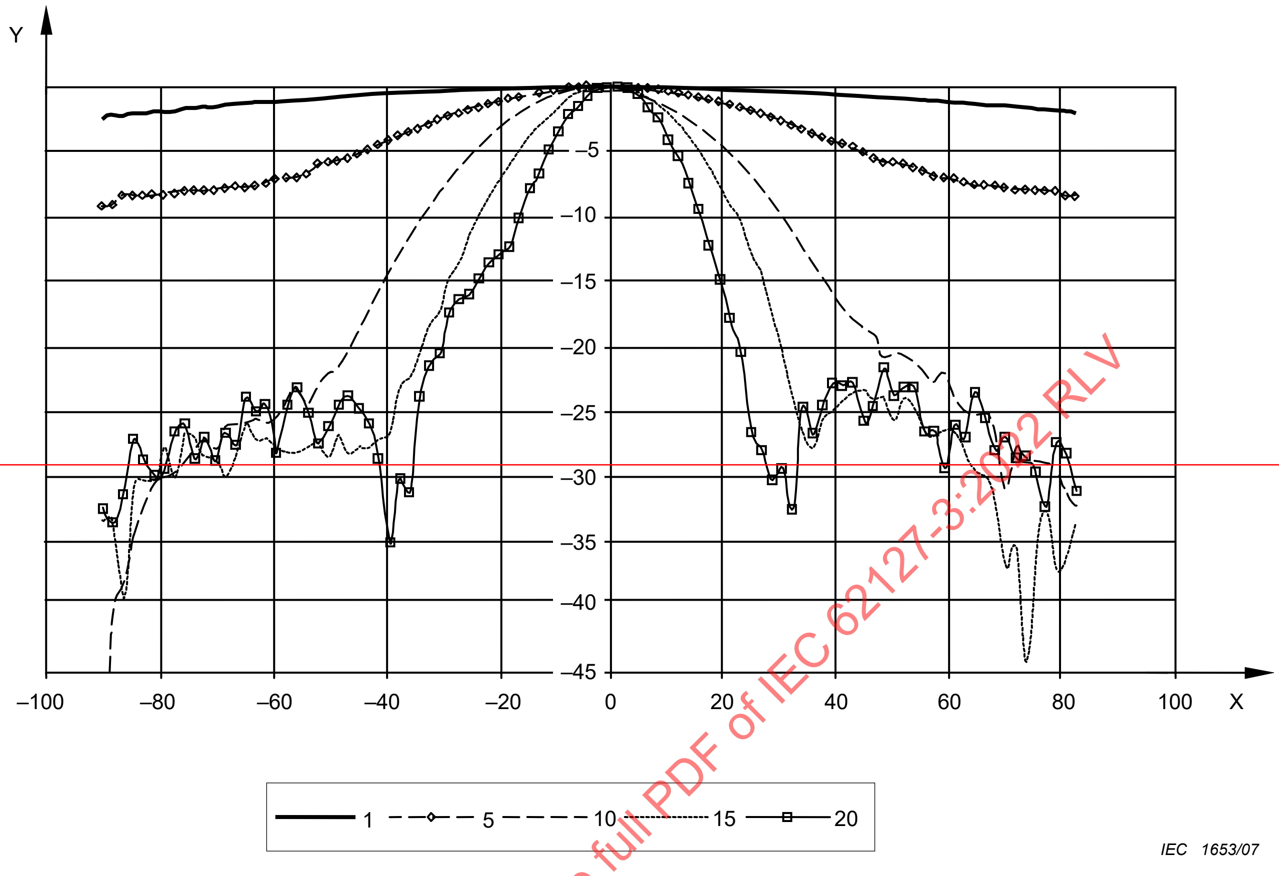
NOTE 2 Considerations explaining the frequency behaviour of needle **hydrophones** are provided in [8].

Needle **hydrophones** that are used to make absolute measures of acoustic pressure should be calibrated at least once every 12 months. The **hydrophone** should be checked against a reference source on a monthly basis so that variations in sensitivity are identified sooner than the annual calibration interval.

A.4 Directional response

The **directional response** of the **hydrophone** was established using the same nonlinear field as that used in the determination of the frequency response above 1 MHz. The **hydrophone** was placed in a mounting fixture that permitted the precise position of the active element to be adjusted. The **hydrophone's** tip was then adjusted so that there was less than 100 ns temporal shift of the recorded waveform when it was rotated in the field. This alignment ensured that the **hydrophone** was not displaced during rotation and therefore that any variations in received signal were due only to the **directional response** of the **hydrophone**. By recording the waveform generated by the **hydrophone** as a function of angle, the **directional response** at a range of frequencies could be established.

The **directional response** of the 0,2 mm needle **hydrophone** at 1 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz, 30 MHz and 40 MHz has been plotted in Figure A.3. Below 1 MHz the directional response becomes increasingly omni-directional and relative amplitude at angles up to ±80° will be with 3 dB of the amplitude at 0°.



~~X angle (degrees)~~

~~Y relative amplitude (dB)~~

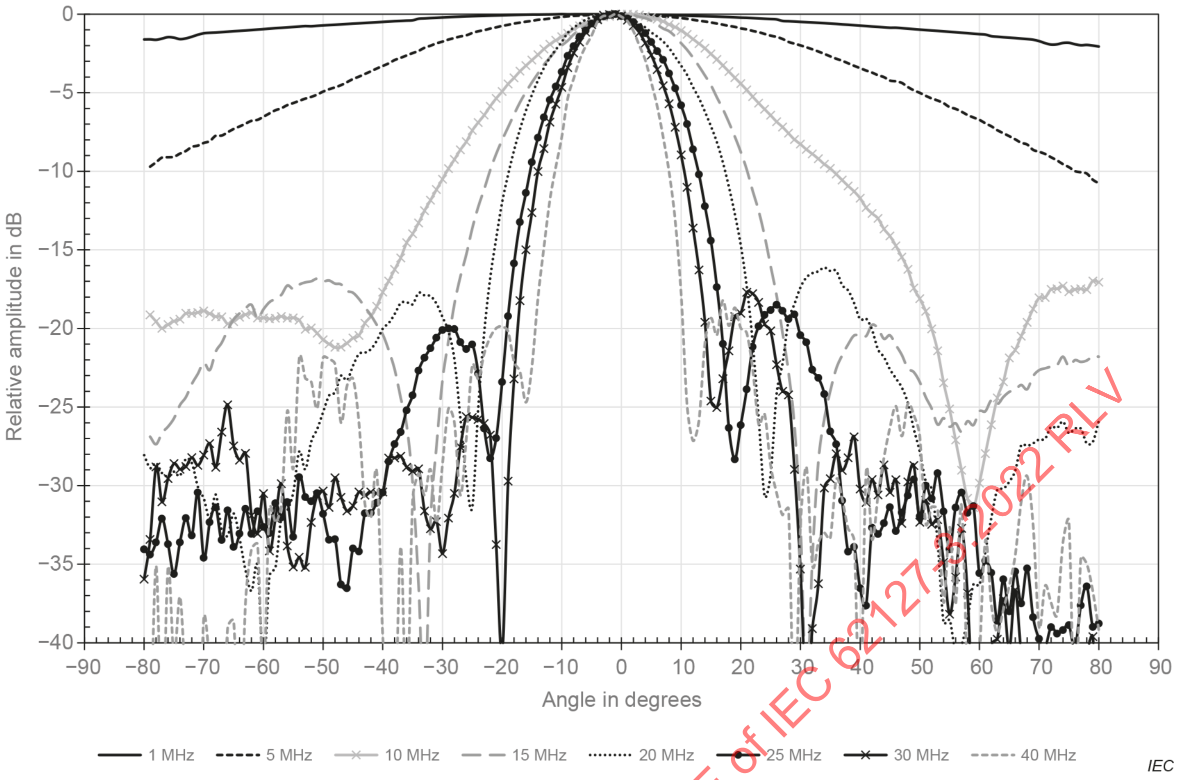


Figure A.3 – Directional response of 0,2 mm needle hydrophone

NOTE Figure A.3 shows curves for only one of the two perpendicular rotational axes covered in 5.5.

~~NOTE 2 The **directional response** curves from 5 MHz to 20 MHz shown in Figure A.2 fulfil the symmetry criterion of 5.5.2. It is not possible to assess this at 1 MHz since the **directional response** curve does not reach the −6 dB limit. See the box below the graph for the frequency identification.~~

~~NOTE 3 The frequency value of 5 MHz agrees with the geometric mean of 1 MHz and 20 MHz within ± 15 %, in accordance with 5.5.1.~~

A.5 Effective ~~radius~~ dimension

~~The **effective radius** of the **hydrophone** was calculated from the angles at which the −3 dB and −6 dB points of a **directional response** curve occur in accordance with the methods described in 5.6. The **effective radii** for the 0,2 mm **hydrophone** was found as~~

~~0,131 mm at 5 MHz; 0,124 mm at 10 MHz; 0,114 mm at 15 MHz; 0,121 mm at 20 MHz.~~

~~NOTE 1 It is the average of a_{h3} and a_{h6} that has been stated here.~~

~~NOTE 2 It is not possible to assess the **effective hydrophone radius** using the specified method at 1 MHz since the **directional response** curve reaches neither the −3 dB nor the −6 dB limits.~~

The 0,2 mm needle **hydrophone** has a circular active element and thus the **effective dimension** quoted is an **effective radius** and is plotted in Figure A.4.

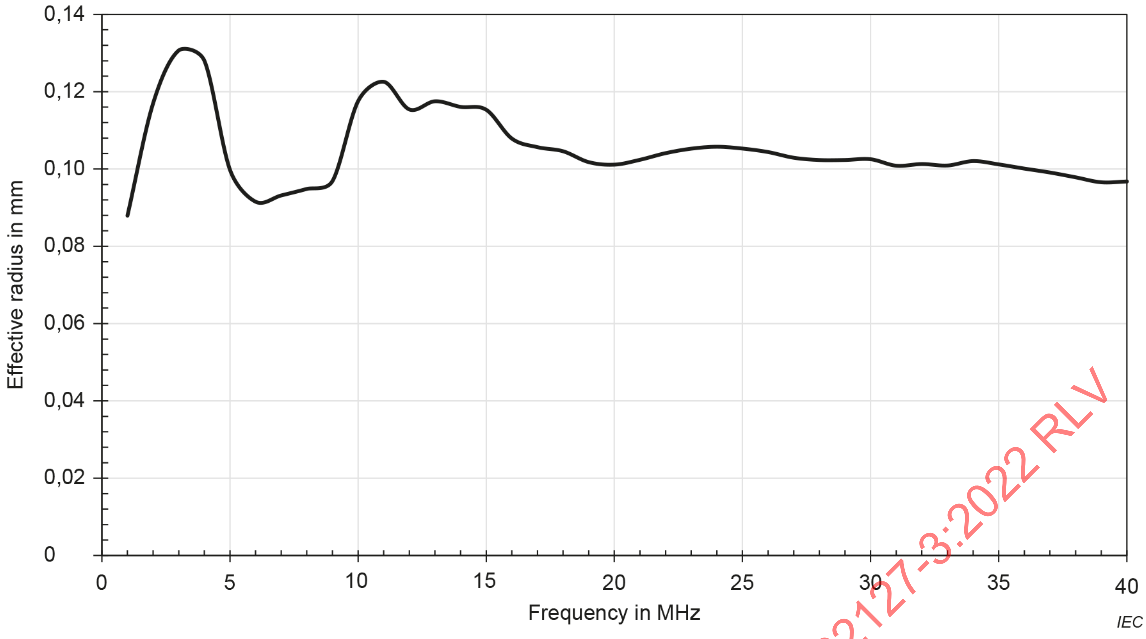


Figure A.4 – Effective radius of 0,2 mm needle hydrophone

The model of **directional response** used to derive the **effective radius** is the unbaffled piston model. It was selected as it was the model that yielded the best fit (in a nonlinear least-squares sense) over the widest frequency range. Whilst the fitting process was conducted over a maximum angular range of ±35°, the fit was found to reliably represent the experimentally derived values over a much wider range, as can be seen in Figure A.5.

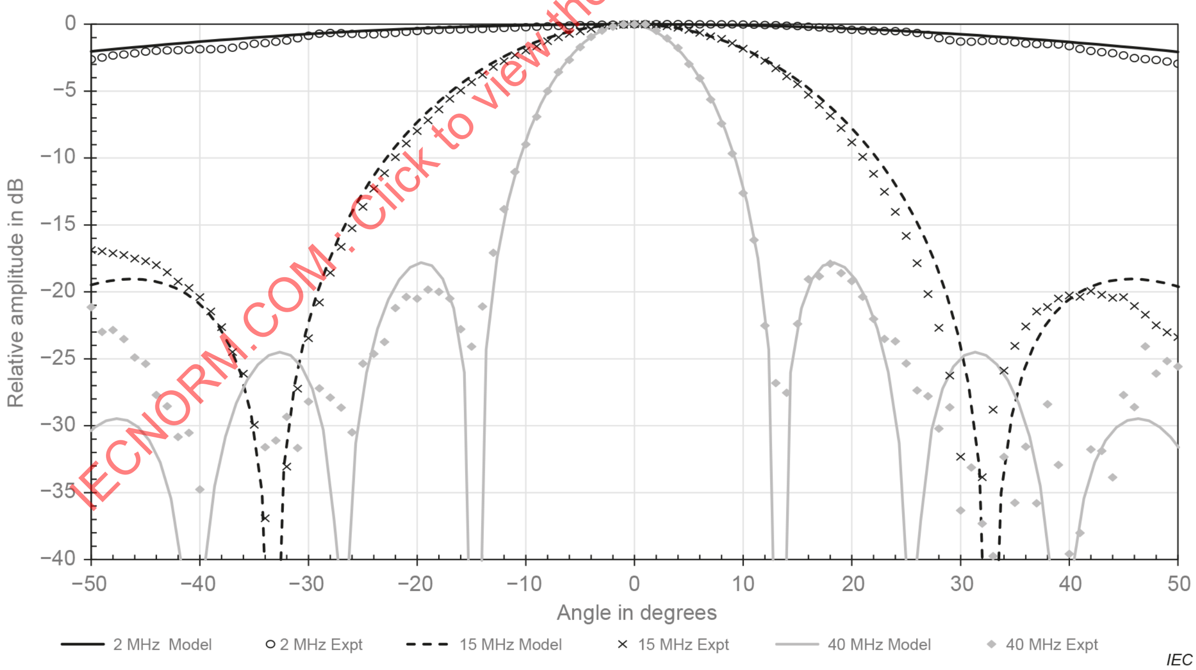


Figure A.5 – Comparison of modelled and experimentally derived directional response

A.6 Dynamic range, linearity and electromagnetic interference

A.6.1 Lower dynamic limit

The noise floor of the **hydrophone assembly** limits the measurement of small acoustic signals. The noise level of the pre-amplifier is approximately 50 μV RMS over a 100 MHz bandwidth. If the **hydrophone** sensitivity is assumed to be 50 nV/Pa, the noise level stated leads to a noise equivalent pressure of 50 μV/50 nV ~~/~~Pa^{-1} = 1 kPa.

NOTE The data acquisition system being used to record the waveforms produced by the **hydrophone** can also limit the minimum recordable signal. For example, an oscilloscope that is limited to a maximum resolution of 0,5 mV will only be able to display signals of amplitude 0,5 mV/50 nV/Pa = 10 kPa or greater.

A.6.2 Upper dynamic limit

Concerning the pressure threshold above which mechanical damage occurs to the **hydrophone**: this **hydrophone** has been designed for use in fields up to 20 MPa. Although **hydrophones** of this type have been used for ultrasonic fields that exceed 50 MPa, there is an elevated risk of damage. The supplier's advice should be sought if the **hydrophone** is to be used in fields containing acoustic pressure levels beyond 20 MPa.

Concerning the pressure beyond which amplifier saturation occurs: the pre-amplifier that is used with this **hydrophone** can start to exhibit nonlinearities when its peak output voltage exceeds 2 000 mV. Taking into account the typical **hydrophone** sensitivity, this corresponds to a pressure of 2 000 mV/50 nV ~~/~~Pa^{-1} = 40 MPa. If pressure fields in excess of this value are to be encountered, contact the **hydrophone** supplier to consider in-line attenuation options.

The linear range is from 1 kPa to 40 MPa.

Possible damage threshold: 20 MPa.

A.7 Electric output characteristics

The electric load condition to which the sensitivity values of Clause A.3 relate is 50 Ω.

A.8 Environmental aspects

This **hydrophone assembly** can be used for measurement over an operating temperature range of 5 °C to 50 °C and can be stored over the range 5 °C to 50 °C. Exposure to temperatures above 60 °C has the potential to cause irreversible damage to the **hydrophone**.

This **hydrophone assembly** has been calibrated at a temperature between 19 °C and 25 °C. The sensitivity of the **hydrophone** will be a function of temperature and an increase in the sensitivity of 0,6 % per degree temperature rise ~~should~~ can be expected.

The **hydrophone assembly** has been designed for complete immersion in water and can easily withstand the hydrostatic pressure caused by 2 m of water. Although the **hydrophone assembly** can be used for prolonged periods (> 48 h) of immersion, the **hydrophone** should be withdrawn from water and allowed to dry whenever it is not in use.

There are no specific operating requirements in terms of water quality for use of this **hydrophone**. However, it is possible that **hydrophone** measurements standards such as IEC 62127-1 or the AIUM/NEMA output measurement standard [9] ~~might~~ have specific requirements for water quality.

NOTE Prolonged immersion in water that has not been deionized (e.g. tap water) can lead to a build-up of deposits on the **hydrophone** tip. Calcium carbonate deposits can be a particular problem in "hard" water areas and will lead to a loss of sensitivity of the **hydrophone**.

Although designed for operation in water, the **hydrophone assembly** can be used in many other liquid media. It should be noted, however, that the calibration of this **hydrophone** was undertaken in water. Other materials present different acoustic impedance loads on the **hydrophone** active element and this is likely to affect the sensitivity of the **hydrophone**. Certain liquids should be avoided due to their chemically aggressive nature. Examples of materials that should be avoided are:

a) concentrated acids (e.g. nitric acid, sulphuric acid);

b) concentrated alkalis (e.g. sodium hydroxide);

c) strong organic solvents (e.g. many aldehydes, many ketones, dimethylene chloride (DMC), dimethylformamide (DMF)).

As supplied, the only materials of the **hydrophone assembly** that are exposed to the surrounding liquid are gold, stainless steel, polytetrafluoroethylene (PTFE), brass and the polyvinyl chloride (PVC) cladding on the pre-amplifier cable. However, if the outer gold electrode on the **hydrophone** becomes damaged, the PVDF and a rigid casting resin ~~might~~ can also become exposed.

Annex B
(informative)

Rationale

B.1 General

This Annex B provides additional information to explain the reasons underpinning non-editorial changes in the second edition of IEC 62127-3 (this document) compared to the first edition (IEC 62127-3:2007 and IEC 62127-3:2007/AMD1:2013).

B.2 Changes to the determination of directional response

In the first edition, **directional response** was determined at the same frequency limits specified in 5.4.1. Some membrane hydrophones have very flat frequency responses that can extend to beyond 100 MHz. Determination of **directional response** at such high frequency is not experimentally practicable; it would require rotation about the **hydrophone** element that introduced a translation much less than a half wavelength at the frequency of interest. At 100 MHz in water, this would require that any translation be much less than 7,5 µm. Instead, this document requires that upper and lower frequencies be as widely separated as practicable, with any deviation from the values in 5.4.1 being specified.

Although the first edition specified the angular range over which **directional response** was evaluated, there was no requirement on the angular increment. For **hydrophone** active elements that were large relative to wavelength, this could lead to considerable change in directivity function for small angular variation. This document requires an angular increment to be selected that ensures no more than 1 dB change between adjacent points.

B.3 Changes to the determination of effective radius

The first edition provided a procedure for the determination of effective radius of a hydrophone that was based upon a simplified process to fit experimentally determined directional response data to a specific theoretical model. The problems with this were three-fold.

a) It implicitly assumes a circular geometry through the use of the word "radius".

b) The method of fitting required hydrophones to have a central peak. It also required that two points on the directivity profile (one on either side of the central peak) were identified at levels −3 dB and −6 dB relative to this peak.

NOTE This had already been identified in Annex A of IEC 62127-3:2007.

c) The method incorporated a fixed theoretical model to represent hydrophone directional response, specifically the radiation pattern of a circular plane piston in a rigid baffle (sometimes referred to as the rigid baffle (RB) model).

To understand why these points are problematic, it is instructive to consider the following.

1) Several commercially available hydrophone designs are based upon rectangular geometries.

2) Many small aperture hydrophones have a directional response (especially at low frequencies) that does not reach −6 dB relative to the peak and possibly does not even fall by 3 dB.

3) Any single point measurement (such as the peak value, or those at levels 3 dB and 6 dB below the peak) could be subject to noise which could affect the determination of **effective hydrophone size**. A more robust method would make use of a more complete set of the available directional response data and be less subject to noise on individual data points [10].

4) Membrane hydrophones, at low frequencies, have well-known off-axis peaks which can be much larger than the central lobe of the directional response [4], [11].
5) Although widely studied in the literature, the rigid baffle piston model has been shown by numerous publications [5], [4], [12], [14] to be a poor representation of the directional response of some hydrophones.
6) The former method was optimized decades ago to provide a simple method that could be easily implemented. Subsequent developments in computational power and algorithms ensure that mathematical software for the calculation of Bessel function and for both linear and nonlinear least squares fitting are widely available.

To address these limitations, the procedure has been revised by separating the fitting process for experimental data from the theoretical model against which it is being compared. Furthermore, the fitting process has been revised so that it can accommodate directivity profiles with large off-axis peaks or with very shallow peaks.

Annex C
(informative)

Membrane hydrophone directivity model

C.1 General

In contrast to other models of directional response that only consider waves propagating within the fluid surrounding the hydrophone, the Bacon [6] model of membrane hydrophone directivity accounts for Lamb wave propagation in the material of the membrane. Consequently, the properties of the membrane material are critical to the predicted response. This Annex C provides additional information to support the model formula in 5.6.2.

C.2 Details of model

The model formula of 5.6.2 a)5) is re-stated here for convenience:

$$D_{\mathrm{H}}(k,a,\theta_1)=\frac{2\mathrm{J}_1[k_1 a\sin(\theta_1)]}{k_1 a\sin(\theta_1)}\cdot\frac{\cos(\theta_1)}{\delta}\cdot\left|\left\{\frac{\cos 2\gamma_2}{\cos^2\theta_2}\left(\delta-\eta\sin^2\gamma_2\right)\right\}\right|\cdot\frac{|g(M,N)|}{|g(M_0,N_0)|}$$

- Within this formula, subscripts 1 and 2 (with the exception of J_1) refer to the properties of the surrounding fluid and the membrane material, respectively.
- $\eta=2\mu(d_{33}-d_{31})$ and
- $\delta=\lambda(d_{31}+d_{32}+d_{33})+2\mu d_{33}$, where λ and μ are the Lamé parameters for the membrane material and d_{31}, d_{32} and d_{33} are the piezo-electric strain constants for the membrane material.
- The function $g(M,N)=\dfrac{M-N-i}{2M+i\left(N^2-M^2+1\right)}$ was originally defined within [13] where a detailed derivation can be found.
- $M=\left(\dfrac{Z_2}{Z_1}\right)\cos^2 2\gamma_2\cot P+\left(\dfrac{Z_{2t}}{Z_1}\right)\sin^2 2\gamma_2\cot Q$.
- $N=\left(\dfrac{Z_2}{Z_1}\right)\cos^2 2\gamma_2\sin P+\left(\dfrac{Z_{2t}}{Z_1}\right)\sin^2 2\gamma_2\sin Q$.
- M_0 and N_0 are for θ_1 = 0°.
- $P=\dfrac{2\pi f}{c_2}h\cos\theta_2$ and $Q=\dfrac{2\pi f}{b_2}h\cos\gamma_2$, where h is the thickness of the membrane.

Angular terms are related via Snell's Law such that $\dfrac{\sin(\theta_1)}{c_1}=\dfrac{\sin(\theta_2)}{c_2}=\dfrac{\sin(\gamma_2)}{b_2}$, where c is longitudinal wave speed and b is shear wave speed.

All expressions for acoustic impedance are scaled by angle of incidence so that $Z_1=\dfrac{\rho_1 c_1}{\cos\theta_1}$, $Z_2=\dfrac{\rho_2 c_2}{\cos\theta_2}$ and $Z_{2t}=\dfrac{\rho_2 b_2}{\cos\gamma_2}$.

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IEC 62127-3

Edition 2.0 2022-12

INTERNATIONAL STANDARD

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Ultrasonics – Hydrophones –
Part 3: Properties of hydrophones for ultrasonic fields

Ultrasons – Hydrophones –
Partie 3: Propriétés des hydrophones pour les champs ultrasoniques

IEC 62127-3:2022-12(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ULTRASONICS – HYDROPHONES –

Part 3: Properties of hydrophones for ultrasonic fields

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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IEC 62127-3 has been prepared by IEC technical committee 87: Ultrasonics. It is an International Standard.

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

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

a) The upper frequency limit of 40 MHz has been removed.
b) Hydrophone sensitivity definitions have been changed to recognize sensitivities as complex-valued quantities.
c) Procedures to determine the effective hydrophone size have been changed according to the rationale outlined in Annex B.
d) Requirements on the frequencies for which the effective hydrophone size shall be provided have been changed to achieve practicality for increased frequency bands.
e) The new Annex B and Annex C have been added.

f) Annex A has been updated to reflect the changes of the normative parts.

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

Draft	Report on voting
87/818/FDIS	87/824/RVD

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

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

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

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

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

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

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

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

INTRODUCTION

The spatial and temporal distribution of acoustic pressure in an ultrasonic field in a liquid medium is commonly determined using miniature ultrasonic **hydrophones**. The properties of these **hydrophones** have been dealt with in a number of IEC standards in various aspects. The purpose of this document is to bring together all these specifications and to establish a common standard on the properties of ultrasonic **hydrophones**. The main **hydrophone** application in this context is the measurement of ultrasonic fields emitted by medical diagnostic equipment in water. Other medical applications are field measurements for therapy equipment such as that used in lithotripsy, high-intensity focused ultrasound (HIFU) and physiotherapy. **Hydrophones** are also used extensively in non-medical applications for both product development and quality control including:

– mapping of the ultrasound field within ultrasonic cleaning baths;
– characterization of acoustic fields used in transmission measurement systems (e.g. ultrasonic spectrometers, ultrasonic attenuation meters and velocimeters);
– characterization of acoustic fields used in reflection measurement systems (e.g. Doppler flowmeters).

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

Underwater **hydrophones** as covered by IEC 60500, IEC 60565-1, and IEC 60565-2 are not included in this document, although there is an overlap in the frequency ranges. Underwater **hydrophones** are used in natural waters, even in the ocean, and this leads to different technical concepts and requirements. In addition, the main direction of acoustic incidence in underwater applications is at various angles and often at right angles to the **hydrophone axis**, whereas in this document it is assumed that the main direction of acoustic incidence is in the direction of the **hydrophone axis**.

Historically, ultrasonic **hydrophones** were used almost exclusively as amplitude sensors. However, the complex-valued nature of a **hydrophone's** system response function is well understood and IEC 62127-1:2022 makes use of this within the deconvolution procedures it contains. In this document, requirements are specified for the amplitude aspect of the **hydrophone** sensitivity and recommendations are provided for the phase aspect which can be derived either via calibration, or via calculation methods that are discussed in IEC 62127-1:2022.

ULTRASONICS – HYDROPHONES –

Part 3: Properties of hydrophones for ultrasonic fields

1 Scope

This part of IEC 62127 specifies relevant **hydrophone** characteristics.

This document 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;
– **hydrophones** with or without an associated pre-amplifier.

2 Normative references

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

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

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

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in IEC 62127-1, IEC 62127-2 and the following apply.

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

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

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

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

[SOURCE: IEC 62127-1:2022, 3.1]

3.2
directional response

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

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

[SOURCE: IEC 60565:2006, 3.5, modified – In the definition, ", generally presented graphically," has been deleted; "electro-acoustic transducer" has been replaced by "hydrophone"; and "radiated or incident sound" has been replaced by "incident plane sound wave,".]

3.3
effective hydrophone size

a_{h}

size of a theoretical receiver **hydrophone** that has a predicted **directional response** function with an angular width equal to the observed angular width

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

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

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

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

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

3.4
electric load impedance

$\underline{Z}_{\mathrm{L}}$

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

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

[SOURCE: IEC 62127-1:2022, 3.22]

3.5
end-of-cable

<**hydrophone** or **hydrophone assembly** with integral output cable> relating to the end of the integral output cable

3.6
end-of-cable

<**hydrophone** or **hydrophone assembly** without integral output cable> relating to the output connector firmly connected with the **hydrophone** or **hydrophone assembly** and not to an extra cable

3.7
end-of-cable loaded sensitivity

$\underline{M}_{\mathrm{L}}(f)$

<of a **hydrophone** or **hydrophone assembly**> quotient of the Fourier transformed **hydrophone** voltage-time signal $\mathcal{F}(u_{\mathrm{L}}(t))$ at the end of any integral cable or output connector of a **hydrophone** or **hydrophone assembly**, when connected to a specified **electric load impedance**, to the Fourier transformed **acoustic pulse waveform** $\mathcal{F}(p(t))$ in the undisturbed

free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_{\mathrm{L}}(f) = \frac{\mathcal{F}(u_{\mathrm{L}}(t))}{\mathcal{F}(p(t))} \tag{1}$$

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

3.8
end-of-cable open-circuit sensitivity
$\underline{M}_{\mathrm{c}}(f)$
<of a **hydrophone**> quotient of the Fourier transformed **hydrophone** open-circuit voltage-time signal $\mathcal{F}(u_{\mathrm{c}}(t))$ at the end of any integral cable or output connector of a **hydrophone** to the Fourier transformed **acoustic pulse waveform** $\mathcal{F}(p(t))$ in the undisturbed free field of a plane wave in the position of the **reference centre** of the **hydrophone** if the **hydrophone** were removed

$$\underline{M}_{\mathrm{c}}(f) = \frac{\mathcal{F}(u_{\mathrm{c}}(t))}{\mathcal{F}(p(t))} \tag{2}$$

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

3.9
end-of-cable loaded sensitivity level
$L_{M_{\mathrm{L}}}(f)$
<of a **hydrophone** or **hydrophone assembly**> twenty times the logarithm to the base 10 of the quotient of the modulus of the **end-of-cable loaded sensitivity** $|\underline{M}_{\mathrm{L}}(f)|$ to a reference sensitivity M_{ref}

$$L_{M_{\mathrm{L}}}(f) = 20\log_{10}\frac{|\underline{M}_{\mathrm{L}}(f)|}{M_{\mathrm{ref}}}\ \mathrm{dB} \tag{3}$$

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

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

3.10
free field
sound field in a homogeneous and isotropic medium in which the effects of boundaries are negligible

[SOURCE: IEC 60565:2006, 3.13]

3.11
hydrophone geometrical size
geometrical size of a hydrophone active element
a_g
size defined by the lateral extents of the active element of a **hydrophone**

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

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

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

3.12
hydrophone
transducer that produces electric signals in response to pressure fluctuations in water

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

3.13
hydrophone assembly
combination of **hydrophone** and **hydrophone pre-amplifier**

3.14
hydrophone axis
nominal symmetry axis of the **hydrophone** active element

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

3.15
hydrophone pre-amplifier
active electronic device connected to, or to be connected to, a particular **hydrophone** and reducing its output impedance

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

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

3.16
reference centre
point on or near a **hydrophone** about which its acoustic receiving sensitivity is defined

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

[SOURCE: IEC 60565:2006, 3.25, modified – In the definition, "transducer" has been replaced by "hydrophone" and "transmitting responses" has been omitted. The note has been replaced.]

3.17
uncertainty
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

Note 1 to entry: See ISO/IEC Guide 98-3:2008 [2], 2.2.3.

[SOURCE: IEC 62127-1:2022, 3.92]

4 List of symbols

a_g	**hydrophone geometrical size**
a_h	**effective hydrophone size**
c	speed of sound in a medium
D_H	model function used during the determination of **effective hydrophone size** from a measured **directional response** of a **hydrophone**
f	frequency
k	wavenumber, equal to $2\pi/\lambda$
$L_{M_L}(f)$	**end-of-cable loaded sensitivity level**
$\underline{M}$	general symbol for the complex **hydrophone** sensitivity, $M = \lvert\underline{M}\rvert$ being its modulus and arg($\underline{M}$) being its argument (equal to phase angle)
$\underline{M}_c$	**end-of-cable open-circuit sensitivity**
$\underline{M}_L$	**end-of-cable loaded sensitivity**
$\underline{Z}_h$	complex electric output impedance of a **hydrophone** or **hydrophone assembly**
$\underline{Z}_L$	**electric load impedance**
θ	angle of incidence of an ultrasonic wave with respect to the **hydrophone axis**

5 Hydrophone characteristics

5.1 General

For a full characterization of the hydrophone performance in the frequency range of this document, the following information is required. Examples of information on hydrophone characteristics are provided in Annex A.

NOTE Determination methods are covered in IEC 62127-2.

5.2 Basic information

The following shall be briefly stated:

– the basic physical principles of the transduction process, the type of sensor material involved, the form and geometrical dimensions (diameter, thickness) of the **hydrophone** active element and the needle diameter in case of a needle **hydrophone**;
– the configuration and design of the **hydrophone**;
– whether or not a pre-amplifier is associated with the **hydrophone**; if the pre-amplifier can be disconnected from the **hydrophone**, clear information shall be given as to which pre-amplifier type belongs to which **hydrophone** type;
– the nominal direction of ultrasonic incidence in relation to the **hydrophone.**

NOTE The last point is important, as it has been found in the literature [3][1] that even with membrane **hydrophones**, the response can change upon reversal of the ultrasonic propagation direction in relation to the **hydrophone**.

The following should be briefly stated:

– the lateral and thickness dimensions of the **hydrophone** active element;
– the frequency of the fundamental thickness resonance of the **hydrophone** active element;
– the size and mass of the **hydrophone**;

1 Numbers in square brackets refer to the Bibliography.

– the recommended **directional response** model (see 5.6.2) appropriate for the **hydrophone**;
– in the case of a membrane **hydrophone**, the acoustic reflection and transmission factor (preferably as a function of frequency);
– information on preamplifier roll-off at low frequencies outside the hydrophone calibration range, if applicable, to support appropriate calibration data extrapolation in accordance with IEC 62127-1:2022.

General note relating to 5.3 and 5.4: if phase information is available, the phase angle (which equals the argument of the complex **hydrophone** sensitivity) should be stated in addition to the sensitivity (which equals the modulus of the complex **hydrophone** sensitivity), as well as the frequency dependence of the phase angle in addition to the frequency dependence of the sensitivity.

5.3 Sensitivity

The modulus of the **end-of-cable** sensitivity of the **hydrophone** or **hydrophone assembly** shall be stated in units of volt per pascal (V/Pa) or in decimal submultiples, or as a logarithmic level in decibels (dB) with reference to a stated sensitivity value.

NOTE 1 Refer to 3.9 regarding the definition of the **end-of-cable loaded sensitivity level**.

If a pre-amplifier contributes to the sensitivity value given, this shall be stated.

It shall be stated whether the sensitivity value given is understood as the **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.

The frequency interval over which the sensitivity is given and over which the **uncertainty** applies shall be stated. For the purposes of this document, sensitivity and **uncertainty** values may be given separately for several frequency intervals.

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

The temperature dependence of the sensitivity shall be given. The **hydrophone** sensitivity shall be stated as a function of the water temperature, at least over the temperature range 19 °C to 25 °C, or the particular water temperature to which the stated sensitivity relates shall be stated together with the temperature coefficient of the sensitivity.

A recommended calibration period shall be provided in the instructions for use. This recommendation applies unless otherwise stated by specific device application standards.

NOTE 2 A calibration period of one year will be appropriate in most cases.

The **reference centre** shall be stated if the sensitivity does not relate to the geometrical centre of the front surface of the **hydrophone** active element.

NOTE 3 This is particularly important for any phase considerations.

The direction of acoustic incidence shall be stated if the sensitivity does not relate to an incidence in the direction of the **hydrophone axis**.

5.4 Frequency response

5.4.1 Stated frequency band

The frequency band claimed for the **hydrophone** or **hydrophone assembly** shall be stated by giving the lower frequency limit and the upper frequency limit. The modulus of the **end-of-cable** sensitivity of the **hydrophone** or **hydrophone assembly** shall be constant over the stated frequency band with a tolerance which shall also be stated.

5.4.2 Frequency dependence

The modulus of the **end-of-cable** sensitivity or sensitivity level of the **hydrophone** or **hydrophone assembly** 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 5.4.1. If it is given as a list of values or as discrete points in a graph, the frequency distance between adjacent points should be low enough so that all important details of the frequency dependence are shown and the sensitivity level does not vary by more than ±1 dB between adjacent points.

The frequency response may be given in terms of absolute sensitivity values or in a relative representation, relative with reference to the absolute sensitivity of the **hydrophone** or **hydrophone assembly** 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 phase of the **end-of-cable** sensitivity may be given as a function of frequency either graphically or as a list of values.

The statement of the frequency response shall refer to the same conditions (i.e. loaded or open-circuit output of the **hydrophone** or **hydrophone assembly**) as the sensitivity statement in accordance with 5.3.

If the **uncertainty** of the sensitivity values in the frequency response representation differs from the **uncertainty** assessment of 5.3, this shall be clearly stated and the new or additional **uncertainty** shall be given.

If the frequency response is given as a list of absolute sensitivity values (**end-of-cable**, loaded or open-circuit), the sensitivity statement in accordance with 5.3 may be omitted.

NOTE 1 The frequency response can depend on the electric load conditions.

NOTE 2 If, in a practical application, the **hydrophone** or **hydrophone assembly** is used with subsequent electronic components such as an amplifier, oscilloscope, etc., the frequency response of the whole system will also be, of course, influenced by the frequency response of these additional components.

5.5 Directional response

5.5.1 General

Directional response, and quantities derived from it, are subject to numerous changes relative to the first edition of IEC 62127-3. Details for the rationale behind these changes can be found in Annex B.

5.5.2 Determination of the directional response

The **directional response** of the **hydrophone** shall be stated at a minimum of three frequencies where the lowest and highest frequencies are as widely separated as possible.

– The lowest frequency at which the **directional response** of the **hydrophone** has been determined should be the lower limit of the frequency band claimed under 5.4.1. If not, the reason(s) for variation shall be stated.

– The highest frequency at which the **directional response** of the **hydrophone** has been determined should be the upper limit of the frequency band claimed under 5.4.1. If not, the reason(s) for variation shall be stated.

NOTE Experimental determination of **directional response** becomes increasingly challenging as frequency increases. Consequently, the highest frequency at which it is practical to determine the **directional response** of the **hydrophone** can be lower than the upper frequency band claimed under 5.4.1. However, **effective hydrophone size** becomes asymptotic as frequency increases. Therefore, it is likely that there is negligible variation in **effective hydrophone size** at frequencies above the highest frequency at which **directional response** has been evaluated.

– The midpoint frequency that is within ±15 % of the geometric mean of the lowest and highest frequencies at which **directional response** of the **hydrophone** has been determined is the third frequency at which the directional response shall be stated. If not, the reason(s) for variation shall be stated.

– If the **hydrophone** has a fundamental thickness resonance within range of the lowest and highest frequencies in this subclause 5.5.2, the **directional response** at this frequency shall also be stated. If not, the reason(s) for variation shall be stated.

The **directional response** should be measured by rotating the **hydrophone** about an axis, which passes through the **reference centre** and 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 smaller. If this method is used, 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. If the active element is non-circular, one of the rotational axes shall be in the direction of the largest dimension. The directions of the rotational axes shall be identified on the **hydrophone** using a mark or in the accompanying literature.

The angular increment shall be chosen to ensure that the variation between adjacent points in the **directional response** is not more than 1 dB.

The measurement of the **directional response** shall be carried out in a quasi-planar wave ultrasonic field.

If the active element is irregular in shape, or has more than two symmetry axes, the **directional response** should be measured around additional axes.

Each of the resulting **directional responses** obtained from the measurements shall be stated.

5.5.3 Symmetry of directional response

If, in any of the **directional response** results obtained, the angle between the direction of maximum response and the **hydrophone axis** is greater than one tenth 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 shall be given. The sensitivity level in the direction of the **hydrophone axis** shall be not lower than the maximum in any other direction minus 2 dB.

The symmetry of any **directional response** should be such that if a normalized sensitivity level of −6 dB occurs for some particular direction subtending a certain angle to the direction of maximum sensitivity (0 dB), then the sensitivity level measured on the opposite side subtending the same angle to the direction of maximum sensitivity shall be −6 dB ± 3 dB.

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

5.6 Effective hydrophone size

5.6.1 General

From the **directional response** results obtained in accordance with 5.5, a value for the **effective hydrophone size** shall be derived and stated as follows.

5.6.2 Model of directional response

When determining the **effective hydrophone size**, the theoretical model against which the experimentally determined **directional response** is being compared shall be stated. To maintain consistency with the first edition of IEC 62127-3, the default model shall be the rigid baffle piston model [see a)1) below] unless clear justification is provided for the choice of an alternative model of directional response. Possible alternative models are given in a)2) to a)5) and in b).

a) For nominally circular shaped **hydrophone** active elements, appropriate models of **directional response** are:

1) rigid baffle piston model

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1\left[ka\sin(\theta)\right]}{ka\sin(\theta)} \tag{4}$$

2) soft baffle piston model [4]

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1\left[ka\sin(\theta)\right]}{ka\sin(\theta)}\cos(\theta) \tag{5}$$

3) unbaffled piston model

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1\left[ka\sin(\theta)\right]}{ka\sin(\theta)}\cdot\frac{1+\cos(\theta)}{2} \tag{6}$$

4) rigid piston model (for probe, needle and fibre-optic hydrophones) [5]

$$D_{\mathrm{H}}(k,a,\theta)=\frac{2\,\mathrm{J}_1\left[ka\sin(\theta)\right]}{ka\sin(\theta)}+\frac{ik\cos(\theta)}{\pi a^2}\int_A\int_B\frac{\mathrm{e}^{-ikx\sin(\theta)}\mathrm{e}^{iks}}{2\pi s}\mathrm{d}A\,\mathrm{d}B \tag{7}$$

where A and B are areas of integration representing the area of the **hydrophone** active element and the end of the probe upon which the **hydrophone** active element is mounted, and s is the distance between the point of observation and the point of integration;

5) Bacon model (for membrane hydrophones including Lamb waves) [6]

$$D_{\mathrm{H}}(k,a,\theta_1)=\frac{2\,\mathrm{J}_1\left[k_1 a\sin(\theta_1)\right]}{k_1 a\sin(\theta_1)}\cdot\frac{\cos(\theta_1)}{\delta}\cdot\left|\left\{\frac{\cos 2\gamma_2}{\cos^2\theta_2}\left(\delta-\eta\sin^2\gamma_2\right)\right\}\right|\cdot\frac{\left|g(M,N)\right|}{\left|g(M_0,N_0)\right|} \tag{8}$$

Further information concerning the terms of this formula is provided in Annex C.

b) For nominally rectangular shaped hydrophone active elements,

$$D_{\mathrm{H}}(k,L,\theta) = \frac{\sin\left[\frac{kL\sin(\theta)}{2}\right]}{\frac{kL\sin(\theta)}{2}} \tag{9}$$

where L is the length of one of the sides of the rectangle.

If the model relies upon one or more properties of the materials involved (for example the Bacon model), the values used for these properties shall be stated.

5.6.3 Fitting of experimental response to theoretical predictions

The **directional response** is expected to exhibit a clear central lobe (possibly with other features such as localized minima to either side of the lobe, or off-axis peaks) and the angular range used for fitting shall be restricted to that which contains the main lobe only and is defined by $\theta_{\mathrm{min}} < \theta < \theta_{\mathrm{max}}$.

Given a centre position of $\theta = 0°$, θ_{limit} is the minimum of:

- the modulus of the first angle at which the **directional response** curve drops 6 dB below the value of the **directional response** at $\theta = 0°$, or
- 35°.

θ_{min} is defined as $-\theta_{\mathrm{limit}}$ in the angular range $\theta < 0°$, and

θ_{max} is defined as θ_{limit} in the angular range $\theta > 0°$.

The **effective hydrophone size** shall be determined as that value of a which minimizes the sum of the squared residual between the magnitude of the model predictions $|D_{\mathrm{H}}(k,a,\theta)|$ and the magnitude of the experimentally determined values $|x(\theta)|$ of the normalized directional response. This shall be repeated at each frequency given in 5.5.2.

$$S = \sum_{\theta=\theta_{\mathrm{min}}}^{\theta_{\mathrm{max}}} \left(|x(\theta)| - |D_{\mathrm{H}}(k,a,\theta)|\right)^2 \tag{10}$$

If the active element is nominally circular, the **effective hydrophone size** shall be given as the average of the two effective radii obtained at the two orthogonal rotational axes.

If the active element is nominally non-circular, the largest of the **effective hydrophone sizes** obtained from the various **directional responses** shall be given as the **effective hydrophone size**.

NOTE The **effective hydrophone size** is usually a function of the frequency. For representative experimental data see Annex A.

5.7 Dynamic range, linearity and electromagnetic interference

The dynamic range of the **hydrophone** or **hydrophone assembly**, i.e. the pressure amplitude range in which the **hydrophone** or **hydrophone assembly** can be used, shall be stated.

This range shall meet at least the following conditions:

a) no mechanical or electrical damage to the **hydrophone** or **hydrophone assembly**;

b) no output saturation;

c) the output signal shall 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 can depend on electromagnetic interference and can thus vary with the electromagnetic conditions at the place of measurement. Ideally, it is be possible to give a noise level representing all other sources of noise except electromagnetic interference.

The linear range of the **hydrophone** or **hydrophone assembly**, i.e. the pressure amplitude range in which the **hydrophone** or **hydrophone assembly** behaves in a linear way according to the condition below, shall be stated.

The condition is as follows. If, on a plot of **end-of-cable** output voltage against **free field** acoustic pressure amplitude, a straight line can be drawn through the origin in such a way that over a certain pressure range the actual voltage values do not deviate from the straight line by more than ±10 %, this range is the linear range of the **hydrophone** or **hydrophone assembly**. This shall be the case for any frequency within the frequency band claimed under 5.4.1.

Information or advice on how to minimize the effects of electromagnetic interference should be provided.

5.8 Electric output characteristics

5.8.1 Hydrophone without pre-amplifier

The **end-of-cable** complex electric output impedance, $\underline{Z}_h$, of the **hydrophone** 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 shall be clearly stated (e.g. the resistance being in series or parallel to the capacitance).

The relation between the complex **end-of-cable loaded sensitivity** and the complex **end-of-cable open-circuit sensitivity** will depend on $\underline{Z}_h$ and $\underline{Z}_L$ and is given by

$$\underline{M}_L = \underline{M}_c \left\{ \underline{Z}_L / (\underline{Z}_h + \underline{Z}_L) \right\} \quad (11)$$

with the moduli being given by

$$|\underline{M}_L| = |\underline{M}_c| \left\{ \frac{\mathrm{Re}^2 \underline{Z}_L + \mathrm{Im}^2 \underline{Z}_L}{\left[\mathrm{Re}\underline{Z}_h + \mathrm{Re}\underline{Z}_L\right]^2 + \left[\mathrm{Im}\underline{Z}_h + \mathrm{Im}\underline{Z}_L\right]^2} \right\}^{1/2} \quad (12)$$

where

$\lvert\underline{M}_L\rvert$	is the modulus of the **end-of-cable loaded sensitivity**;
$\lvert\underline{M}_c\rvert$	is the modulus of the **end-of-cable open-circuit sensitivity**;
"Re" and "Im"	are the real and imaginary parts of the relevant quantity.

Formula (11) and Formula (12) may 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.

NOTE Formula (11) and Formula (12) apply to a frequency domain consideration. In practical **hydrophone** applications with ultrasonic pulses, time domain considerations (temporal convolution and deconvolution) would need to be taken into account.

For a **hydrophone** without a pre-amplifier, the **hydrophone end-of-cable** sensitivity can be stated as either loaded sensitivity or open-circuit sensitivity.

If the **end-of-cable** sensitivity is stated as loaded sensitivity, the relevant electric load conditions (**electric load impedance** or equivalent network components) to which the sensitivity values relate shall be stated. If the **hydrophone** is used under different load conditions, the sensitivity shall be corrected in accordance with Formula (12).

If the **end-of-cable** sensitivity is given as open-circuit sensitivity and if the **hydrophone** output is connected to a finite **electric load impedance**, the sensitivity shall be corrected in accordance with Formula (12).

5.8.2 Hydrophone assembly

For a **hydrophone assembly**, the **end-of-cable** sensitivity shall be stated as loaded sensitivity, and the relevant electric load conditions (**electric load impedance** or equivalent network components) to which the sensitivity values relate shall be stated. If the **hydrophone assembly** is used under different load conditions, the sensitivity needs to be corrected.

5.8.3 Output lead configuration

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

5.9 Environmental aspects

5.9.1 Temperature range

The permitted operating and storage temperature range for the **hydrophone** or **hydrophone assembly** shall be stated by the manufacturer.

5.9.2 Water tightness

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

5.9.3 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 of **hydrophone** properties refer shall be stated.

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

5.9.4 Exposed material

Types of material (metal, rubber, casting resin, etc.) exposed to the liquid in which the **hydrophone** is allowed to be used shall be stated. All exposed **hydrophone** parts shall be made from corrosion-compatible and corrosion-resistant materials. In particular, the use of a variety of metals for exposed components should be avoided to avert the possible occurrence of galvanic corrosion.

Exposed metal parts of the **hydrophone** housing and electrostatic shield shall be connected to the cable screen.

5.10 Guidance manual

A detailed guidance manual shall be provided with the **hydrophone** or **hydrophone assembly**.

In addition to the information specified in 5.2 to 5.9, the manual should include the following:

– a drawing that shows the geometrical shape and size of the **hydrophone** or **hydrophone assembly**;
– guidance on the proper and safe use of the **hydrophone** or **hydrophone assembly**, including soak time, temperature range and maximum ultrasonic pressure;
– typical impedance plot and amplifier gain plot (if applicable) as a function of frequency.

5.11 List of hydrophone characteristics

The required information on **hydrophone** properties is summarized in the following list:

– basic information, such as the acoustically active material, geometrical dimensions (lateral and thickness) of active element and whether or not a pre-amplifier is included;
– **hydrophone** sensitivity;
– frequency response (of the sensitivity) and the fundamental thickness resonance frequency;
– **directional response** and **effective hydrophone size**;
– dynamic range and linear range;
– electric output impedance and lead configuration;
– environmental aspects.

Annex A
(informative)

Examples of information on hydrophone properties

A.1 General

This Annex A provides sample information on a 0,2 mm needle **hydrophone** that is designed to be used in conjunction with a submersible **hydrophone pre-amplifier**. Wherever acoustic properties of the **hydrophone** are stated, they relate to the **hydrophone/pre-amplifier** combination (**hydrophone assembly**).

NOTE The material given in this Annex A only demonstrates how information is to be presented. It is not an endorsement of a specific product.

A.2 Basic information

Basic information for the example of a 0,2 mm nominal diameter needle hydrophone assembly is provided in Table A.1.

Table A.1 – Example of basic information for 0,2 mm needle hydrophone assembly

Required characteristic information	Example 0,2 mm needle hydrophone
Transduction method	Piezoelectric conversion
Sensor material	Polyvinylidene fluoride (PVDF)
Active element	Circular element, diameter 0,2 mm, thickness 9 µm
Piezo-film thickness resonance frequency	53 MHz
Typical sensitivity in the range 5 MHz to 35 MHz	50 nV/Pa (further data in Clause A.3)
Outer diameter of needle shaft	0,5 mm
Mass of **hydrophone**	1,5 g
Length of **hydrophone**	Overall: 55 mm, needle shaft: 35 mm
Pre-amplifier	**Hydrophone** to be used in conjunction with a submersible pre-amplifier with generic model number NNNN
Nominal output impedance	50 Ω
Intended orientation in use (nominal direction of ultrasound incidence)	Needle tip pointing directly towards the acoustic source

A.3 Sensitivity and frequency response

This frequency response of the **hydrophone** was obtained by two substitution calibrations; reported responses are the **end-of-cable loaded sensitivity** for the needle **hydrophone** used in conjunction with its appropriate pre-amplifier, when loaded by 50 Ω. For the response in the range 1 MHz to 40 MHz, the procedure follows the method described by Smith and Bacon [7]. This method uses an ultrasonic source that produced a highly shocked waveform containing a wide harmonic content with many components at integer multiples of the fundamental frequency of 1 MHz. This enables a calibration of the **hydrophone** from 1 MHz to 40 MHz in 1 MHz increments. The data are displayed in Figure A.1. Spline interpolation was used to produce the data between the calibrated sensitivities.

Below 1 MHz, frequency response was also determined by substitution calibration, but with a different source. Here a broadband piezo-composite transducer was subject to an impulse excitation signal and spectral information was extracted in the range 100 kHz to 1 MHz in 50 kHz increments. The data are displayed in Figure A.2.

The **hydrophone** was calibrated at (20 ± 2) °C.

NOTE 1 The temperature coefficient of the sensitivity is given in Clause A.8.

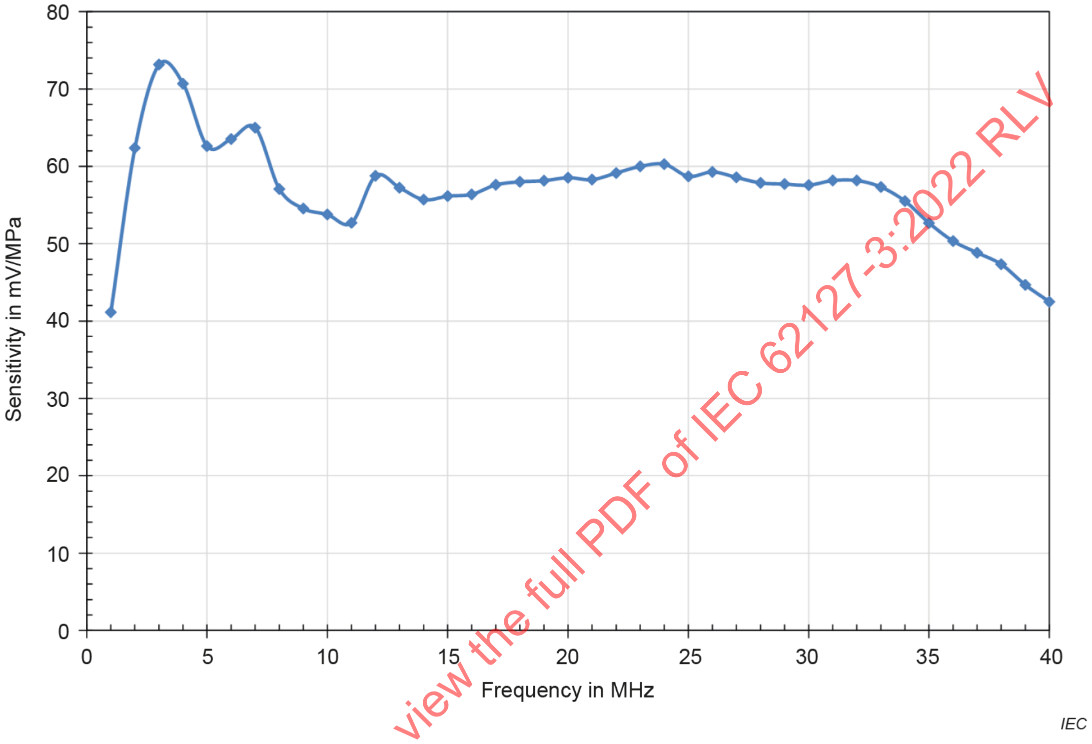

Figure A.1 – Frequency response of 0,2 mm needle hydrophone in the range 1 MHz to 40 MHz

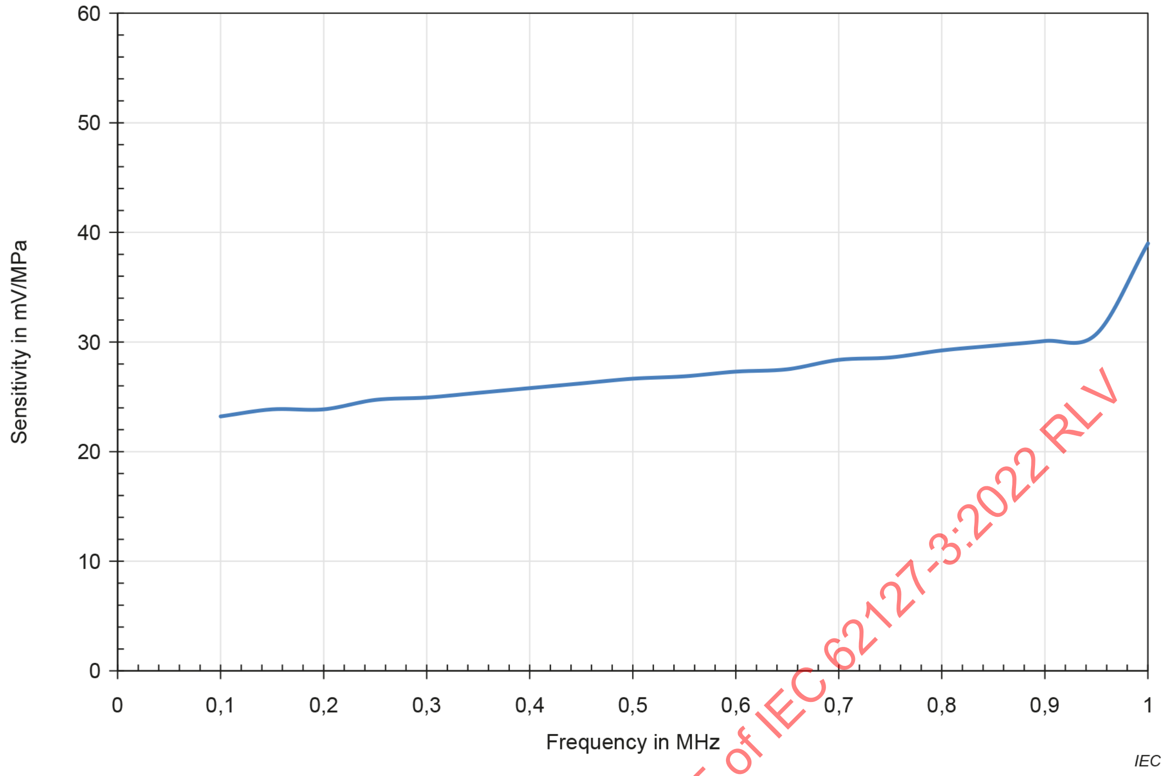

Figure A.2 – Frequency response of 0,2 mm needle hydrophone in the range 100 kHz to 1 MHz

Mean **hydrophone** sensitivity in the range 1 MHz to 40 MHz: 50 mV/MPa

Mean **hydrophone** sensitivity in the range 0,1 MHz to 0,95 MHz: 27 mV/MPa

Sensitivity level variation between individual probes: approximately ±3 dB

Hydrophone frequency band: 0,1 MHz to 40 MHz

Measurement **uncertainty**:

Frequency range	**Expanded uncertainty**
0,1 MHz to 1 MHz	11 %
1 MHz to 8 MHz	14 %
9 MHz to 20 MHz	17 %
21 MHz to 40 MHz	19 %

The measurement **uncertainty** for the frequency response measurement was determined in accordance with the methods established in [2]. One of the main **uncertainty** contributions is the **uncertainty** due to the calibration of the reference **hydrophone** used in the calibration, which itself is traceable to national primary standards.

NOTE 2 Considerations explaining the frequency behaviour of needle **hydrophones** are provided in [8].

Needle **hydrophones** that are used to make absolute measures of acoustic pressure should be calibrated at least once every 12 months. The **hydrophone** should be checked against a reference source on a monthly basis so that variations in sensitivity are identified sooner than the annual calibration interval.

A.4 Directional response

The **directional response** of the **hydrophone** was established using the same nonlinear field as that used in the determination of the frequency response above 1 MHz. The **hydrophone** was placed in a mounting fixture that permitted the precise position of the active element to be adjusted. The **hydrophone's** tip was then adjusted so that there was less than 100 ns temporal shift of the recorded waveform when it was rotated in the field. This alignment ensured that the **hydrophone** was not displaced during rotation and therefore that any variations in received signal were due only to the **directional response** of the **hydrophone**. By recording the waveform generated by the **hydrophone** as a function of angle, the **directional response** at a range of frequencies could be established.

The **directional response** of the 0,2 mm needle **hydrophone** at 1 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz, 30 MHz and 40 MHz has been plotted in Figure A.3. Below 1 MHz the directional response becomes increasingly omni-directional and relative amplitude at angles up to ±80° will be with 3 dB of the amplitude at 0°.

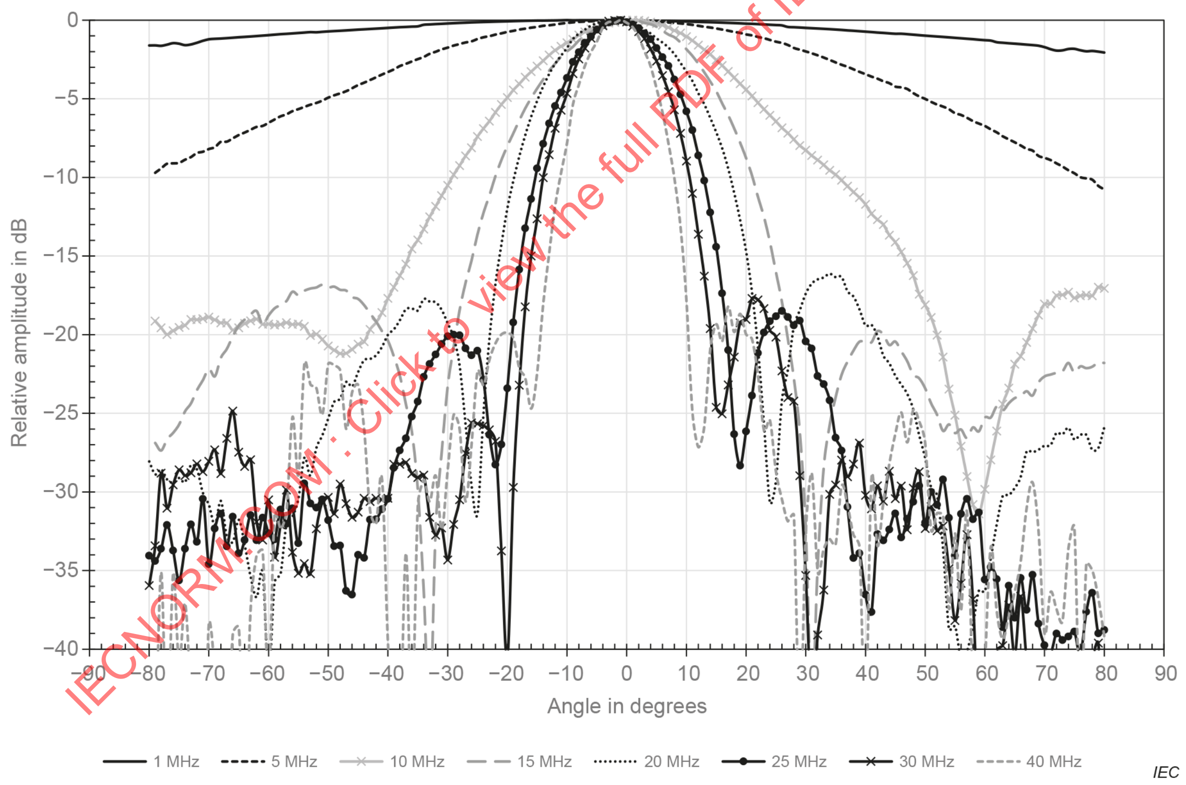

Figure A.3 – Directional response of 0,2 mm needle hydrophone

NOTE Figure A.3 shows curves for only one of the two perpendicular rotational axes covered in 5.5.

A.5 Effective dimension

The 0,2 mm needle **hydrophone** has a circular active element and thus the **effective dimension** quoted is an **effective radius** and is plotted in Figure A.4.

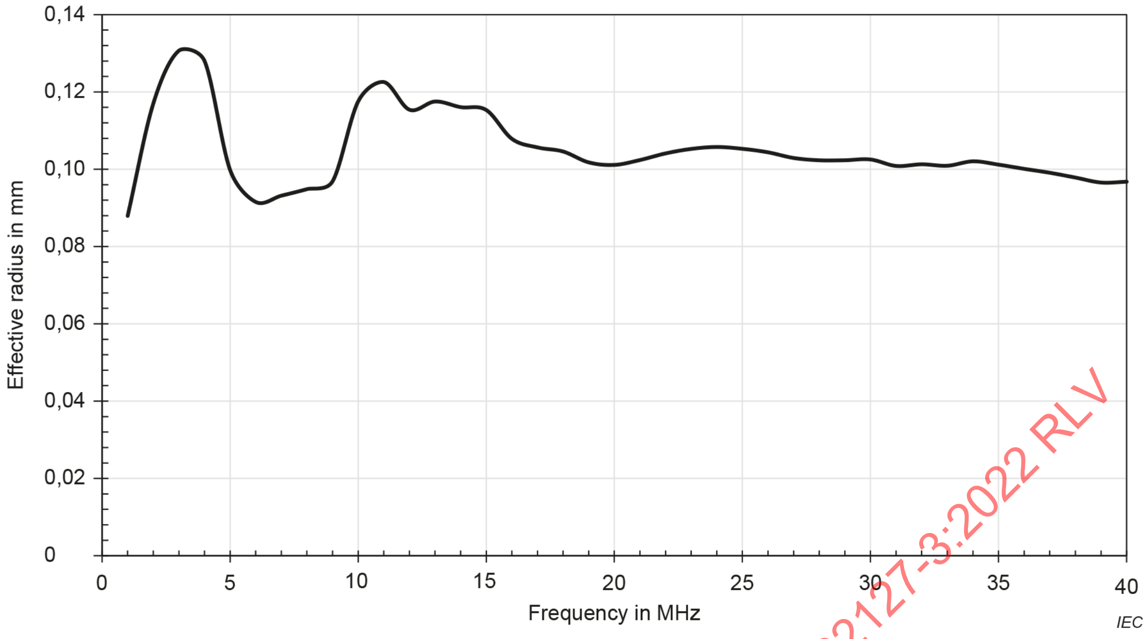

Figure A.4 – Effective radius of 0,2 mm needle hydrophone

The model of **directional response** used to derive the **effective radius** is the unbaffled piston model. It was selected as it was the model that yielded the best fit (in a nonlinear least-squares sense) over the widest frequency range. Whilst the fitting process was conducted over a maximum angular range of ±35°, the fit was found to reliably represent the experimentally derived values over a much wider range, as can be seen in Figure A.5.

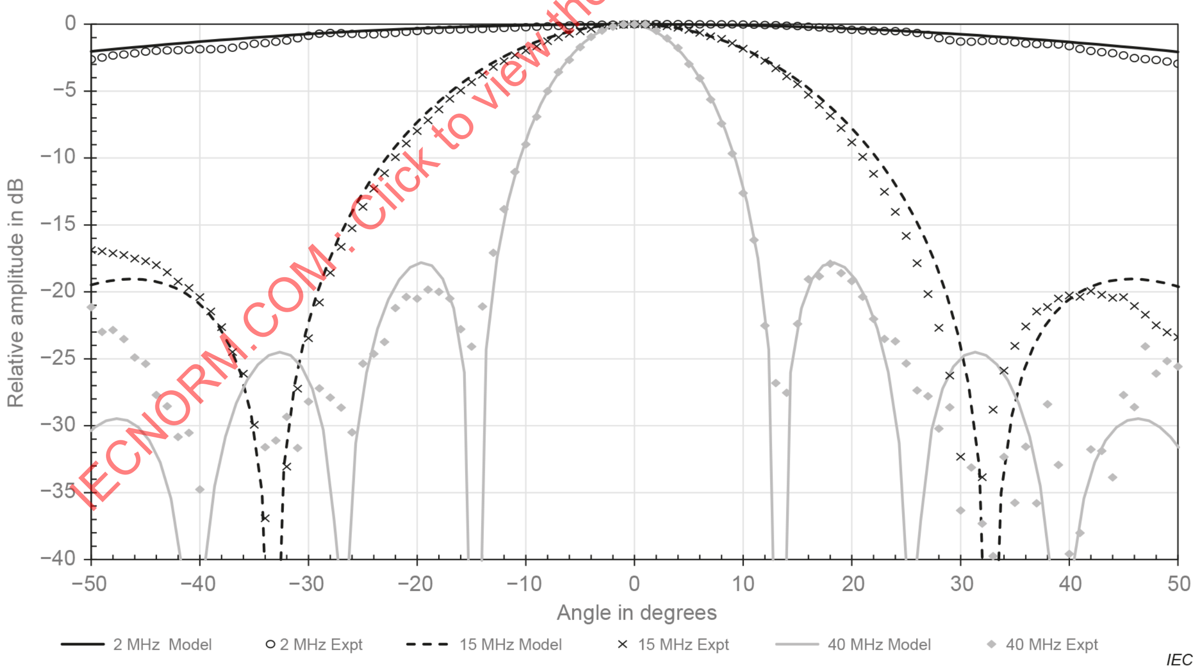

Figure A.5 – Comparison of modelled and experimentally derived directional response

A.6 Dynamic range, linearity and electromagnetic interference

A.6.1 Lower dynamic limit

The noise floor of the **hydrophone assembly** limits the measurement of small acoustic signals. The noise level of the pre-amplifier is approximately 50 µV RMS over a 100 MHz bandwidth. If the **hydrophone** sensitivity is assumed to be 50 nV/Pa, the noise level stated leads to a noise equivalent pressure of 50 µV/50 nV Pa^{-1} = 1 kPa.

NOTE The data acquisition system being used to record the waveforms produced by the **hydrophone** can also limit the minimum recordable signal. For example, an oscilloscope that is limited to a maximum resolution of 0,5 mV will only be able to display signals of amplitude 0,5 mV/50 nV/Pa = 10 kPa or greater.

A.6.2 Upper dynamic limit

Concerning the pressure threshold above which mechanical damage occurs to the **hydrophone**: this **hydrophone** has been designed for use in fields up to 20 MPa. Although **hydrophones** of this type have been used for ultrasonic fields that exceed 50 MPa, there is an elevated risk of damage. The supplier's advice should be sought if the **hydrophone** is to be used in fields containing acoustic pressure levels beyond 20 MPa.

Concerning the pressure beyond which amplifier saturation occurs: the pre-amplifier that is used with this **hydrophone** can start to exhibit nonlinearities when its peak output voltage exceeds 2 000 mV. Taking into account the typical **hydrophone** sensitivity, this corresponds to a pressure of 2 000 mV/50 nV Pa^{-1} = 40 MPa. If pressure fields in excess of this value are to be encountered, contact the **hydrophone** supplier to consider in-line attenuation options.

The linear range is from 1 kPa to 40 MPa.

Possible damage threshold: 20 MPa.

A.7 Electric output characteristics

The electric load condition to which the sensitivity values of Clause A.3 relate is 50 Ω.

A.8 Environmental aspects

This **hydrophone assembly** can be used for measurement over an operating temperature range of 5 °C to 50 °C and can be stored over the range 5 °C to 50 °C. Exposure to temperatures above 60 °C has the potential to cause irreversible damage to the **hydrophone**.

This **hydrophone assembly** has been calibrated at a temperature between 19 °C and 25 °C. The sensitivity of the **hydrophone** will be a function of temperature and an increase in the sensitivity of 0,6 % per degree temperature rise can be expected.

The **hydrophone assembly** has been designed for complete immersion in water and can easily withstand the hydrostatic pressure caused by 2 m of water. Although the **hydrophone assembly** can be used for prolonged periods (> 48 h) of immersion, the **hydrophone** should be withdrawn from water and allowed to dry whenever it is not in use.

There are no specific operating requirements in terms of water quality for use of this **hydrophone**. However, it is possible that **hydrophone** measurements standards such as IEC 62127-1 or the AIUM/NEMA output measurement standard [9] have specific requirements for water quality.

NOTE Prolonged immersion in water that has not been deionized (e.g. tap water) can lead to a build-up of deposits on the **hydrophone** tip. Calcium carbonate deposits can be a particular problem in "hard" water areas and will lead to a loss of sensitivity of the **hydrophone**.

Although designed for operation in water, the **hydrophone assembly** can be used in many other liquid media. It should be noted, however, that the calibration of this **hydrophone** was undertaken in water. Other materials present different acoustic impedance loads on the **hydrophone** active element and this is likely to affect the sensitivity of the **hydrophone**. Certain liquids should be avoided due to their chemically aggressive nature. Examples of materials that should be avoided are:

a) concentrated acids (e.g. nitric acid, sulphuric acid);

b) concentrated alkalis (e.g. sodium hydroxide);

c) strong organic solvents (e.g. many aldehydes, many ketones, dimethylene chloride (DMC), dimethylformamide (DMF)).

As supplied, the only materials of the **hydrophone assembly** that are exposed to the surrounding liquid are gold, stainless steel, polytetrafluoroethylene (PTFE), brass and the polyvinyl chloride (PVC) cladding on the pre-amplifier cable. However, if the outer gold electrode on the **hydrophone** becomes damaged, the PVDF and a rigid casting resin can also become exposed.

Annex B
(informative)

Rationale

B.1 General

This Annex B provides additional information to explain the reasons underpinning non-editorial changes in the second edition of IEC 62127-3 (this document) compared to the first edition (IEC 62127-3:2007 and IEC 62127-3:2007/AMD1:2013).

B.2 Changes to the determination of directional response

In the first edition, **directional response** was determined at the same frequency limits specified in 5.4.1. Some membrane hydrophones have very flat frequency responses that can extend to beyond 100 MHz. Determination of **directional response** at such high frequency is not experimentally practicable; it would require rotation about the **hydrophone** element that introduced a translation much less than a half wavelength at the frequency of interest. At 100 MHz in water, this would require that any translation be much less than 7,5 µm. Instead, this document requires that upper and lower frequencies be as widely separated as practicable, with any deviation from the values in 5.4.1 being specified.

Although the first edition specified the angular range over which **directional response** was evaluated, there was no requirement on the angular increment. For **hydrophone** active elements that were large relative to wavelength, this could lead to considerable change in directivity function for small angular variation. This document requires an angular increment to be selected that ensures no more than 1 dB change between adjacent points.

B.3 Changes to the determination of effective radius

The first edition provided a procedure for the determination of effective radius of a hydrophone that was based upon a simplified process to fit experimentally determined directional response data to a specific theoretical model. The problems with this were three-fold.

a) It implicitly assumes a circular geometry through the use of the word "radius".

b) The method of fitting required hydrophones to have a central peak. It also required that two points on the directivity profile (one on either side of the central peak) were identified at levels −3 dB and −6 dB relative to this peak.

NOTE This had already been identified in Annex A of IEC 62127-3:2007.

c) The method incorporated a fixed theoretical model to represent hydrophone directional response, specifically the radiation pattern of a circular plane piston in a rigid baffle (sometimes referred to as the rigid baffle (RB) model).

To understand why these points are problematic, it is instructive to consider the following.

1) Several commercially available hydrophone designs are based upon rectangular geometries.

2) Many small aperture hydrophones have a directional response (especially at low frequencies) that does not reach −6 dB relative to the peak and possibly does not even fall by 3 dB.

3) Any single point measurement (such as the peak value, or those at levels 3 dB and 6 dB below the peak) could be subject to noise which could affect the determination of **effective hydrophone size**. A more robust method would make use of a more complete set of the available directional response data and be less subject to noise on individual data points [10].

4) Membrane hydrophones, at low frequencies, have well-known off-axis peaks which can be much larger than the central lobe of the directional response [4], [11].

5) Although widely studied in the literature, the rigid baffle piston model has been shown by numerous publications [5], [4], [12], [14] to be a poor representation of the directional response of some hydrophones.

6) The former method was optimized decades ago to provide a simple method that could be easily implemented. Subsequent developments in computational power and algorithms ensure that mathematical software for the calculation of Bessel function and for both linear and nonlinear least squares fitting are widely available.

To address these limitations, the procedure has been revised by separating the fitting process for experimental data from the theoretical model against which it is being compared. Furthermore, the fitting process has been revised so that it can accommodate directivity profiles with large off-axis peaks or with very shallow peaks.

Annex C
(informative)

Membrane hydrophone directivity model

C.1 General

In contrast to other models of directional response that only consider waves propagating within the fluid surrounding the hydrophone, the Bacon [6] model of membrane hydrophone directivity accounts for Lamb wave propagation in the material of the membrane. Consequently, the properties of the membrane material are critical to the predicted response. This Annex C provides additional information to support the model formula in 5.6.2.

C.2 Details of model

The model formula of 5.6.2 a)5) is re-stated here for convenience:

$$D_{\mathrm{H}}(k,a,\theta_1)=\frac{2\mathrm{J}_1[k_1 a\sin(\theta_1)]}{k_1 a\sin(\theta_1)}\cdot\frac{\cos(\theta_1)}{\delta}\cdot\left|\left\{\frac{\cos 2\gamma_2}{\cos^2\theta_2}\left(\delta-\eta\sin^2\gamma_2\right)\right\}\right|\cdot\frac{|g(M,N)|}{|g(M_0,N_0)|}$$

- Within this formula, subscripts 1 and 2 (with the exception of J_1) refer to the properties of the surrounding fluid and the membrane material, respectively.
- $\eta=2\mu(d_{33}-d_{31})$ and
- $\delta=\lambda(d_{31}+d_{32}+d_{33})+2\mu d_{33}$, where λ and μ are the Lamé parameters for the membrane material and d_{31}, d_{32} and d_{33} are the piezo-electric strain constants for the membrane material.
- The function $g(M,N)=\dfrac{M-N-i}{2M+i(N^2-M^2+1)}$ was originally defined within [13] where a detailed derivation can be found.
- $M=\left(\dfrac{Z_2}{Z_1}\right)\cos^2 2\gamma_2\cot P+\left(\dfrac{Z_{2t}}{Z_1}\right)\sin^2 2\gamma_2\cot Q$.
- $N=\left(\dfrac{Z_2}{Z_1}\right)\cos^2 2\gamma_2\sin P+\left(\dfrac{Z_{2t}}{Z_1}\right)\sin^2 2\gamma_2\sin Q$.
- M_0 and N_0 are for θ_1 = 0°.
- $P=\dfrac{2\pi f}{c_2}h\cos\theta_2$ and $Q=\dfrac{2\pi f}{b_2}h\cos\gamma_2$, where h is the thickness of the membrane.

Angular terms are related via Snell's Law such that $\dfrac{\sin(\theta_1)}{c_1}=\dfrac{\sin(\theta_2)}{c_2}=\dfrac{\sin(\gamma_2)}{b_2}$, where c is longitudinal wave speed and b is shear wave speed.

All expressions for acoustic impedance are scaled by angle of incidence so that $Z_1=\dfrac{\rho_1 c_1}{\cos\theta_1}$, $Z_2=\dfrac{\rho_2 c_2}{\cos\theta_2}$ and $Z_{2t}=\dfrac{\rho_2 b_2}{\cos\gamma_2}$.

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IEC 60565-2, *Underwater acoustics – Hydrophones – Calibration of hydrophones – Part 2: Procedures for low frequency pressure calibration*

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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ULTRASONS – HYDROPHONES –

Partie 3: Propriétés des hydrophones pour les champs ultrasoniques

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8) L'attention est attirée sur les références normatives citées dans cette publication. L'utilisation de publications référencées est obligatoire pour une application correcte de la présente publication.
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L'IEC 62127-3 a été établie par le comité d'études 87 de l'IEC: Ultrasons. Il s'agit d'une Norme internationale.

Cette deuxième édition annule et remplace la première édition parue en 2007 et son amendement 1:2013. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente.

a) La limite de fréquence supérieure de 40 MHz a été supprimée.
b) Les définitions de la sensibilité de l'hydrophone ont été modifiées afin de reconnaître les sensibilités comme des grandeurs à valeur complexe.
c) Les procédures de détermination de la taille efficace de l'hydrophone ont été modifiées conformément à la justification donnée à l'Annexe B.

d) Les exigences relatives aux fréquences pour lesquelles doit être fournie la taille efficace de l'hydrophone ont été modifiées afin de tenir compte des bandes de fréquences supérieures.

e) De nouvelles annexes ont été ajoutées (Annexe B et Annexe C).

f) L'Annexe A a été mise à jour afin de refléter les modifications apportées aux parties normatives.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
87/818/FDIS	87/824/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/publications.

Une liste de toutes les parties de la série IEC 62127, publiées sous le titre général *Ultrasons – Hydrophones*, se trouve sur le site web de l'IEC.

NOTE Les termes en **gras** dans le texte sont définis à l'Article 3.

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INTRODUCTION

La répartition spatiale et temporelle de la pression acoustique d'un champ ultrasonique en milieu liquide est généralement déterminée à l'aide d'**hydrophones** à ultrasons miniatures. Les propriétés de ces **hydrophones** ont été traitées sous différents aspects dans plusieurs normes de l'IEC. Le présent document a pour objet de compiler l'ensemble de ces spécifications et d'établir une norme commune pour les propriétés des **hydrophones** à ultrasons. Dans ce cadre, la principale application des **hydrophones** est la mesure des champs ultrasoniques émis par les appareils de diagnostic médical immergés dans l'eau. D'autres applications médicales consistent à mesurer les champs des appareils de thérapie comme ceux utilisés en lithotritie, en ultrasons focalisés de haute intensité (UFHI) et en physiothérapie. Les **hydrophones** sont également utilisés couramment dans les applications non médicales pour le développement de produits et le contrôle qualité, notamment:

– la cartographie du champ ultrasonique dans les bains de nettoyage à ultrasons;
– la caractérisation des champs acoustiques utilisés dans les systèmes de mesure de la transmission (spectromètres à ultrasons, appareils de mesure d'affaiblissement ultrasoniques et vélocimètres, par exemple);
– la caractérisation des champs acoustiques utilisés dans les systèmes de mesure par réflexion (débitmètres Doppler, par exemple).

Si le terme **hydrophone** peut être utilisé dans un sens plus large, il fait référence ici aux **hydrophones** piézoélectriques miniatures. Il s'agit d'un type d'instrument de mesure utilisé aujourd'hui dans différents domaines des ultrasons, notamment pour caractériser de manière quantitative la structure du champ des instruments de diagnostic médical. Concernant les autres types de capteurs de pression, comme les capteurs fibroniques, certaines exigences du présent document s'appliquent à des capteurs particuliers seulement. Si les méthodes de mesure de champ ultérieures privilégient d'autres types d'**hydrophones**, leurs propriétés devront être traitées dans une version révisée du présent document ou dans un document distinct.

Les **hydrophones** en milieu sous-marin couverts par l'IEC 60500, l'IEC 60565-1 et l'IEC 60565-2 ne sont pas traités dans le présent document, malgré un chevauchement dans les plages de fréquences. Les **hydrophones** en milieu sous-marin sont utilisés en eaux naturelles, et même dans l'océan, ce qui aboutit à différents concepts techniques et différentes exigences. En outre, la direction principale de l'incidence acoustique dans les applications sous-marines est décrite par plusieurs angles et souvent par des angles droits par rapport à l'**axe de l'hydrophone**, alors que le présent document admet par hypothèse que la direction principale de l'incidence acoustique est la direction de l'**axe de l'hydrophone**.

Historiquement, les **hydrophones** à ultrasons étaient pratiquement utilisés exclusivement comme détecteurs d'amplitude. Cependant, la nature à valeur complexe de la fonction de réponse du système d'un **hydrophone** est bien comprise et l'IEC 62127-1:2022 l'utilise dans ses procédures de déconvolution. Dans le présent document, les exigences sont spécifiées en se fondant sur les aspects liés à l'amplitude de la sensibilité de l'**hydrophone** et des recommandations sont fournies pour les aspects liés à la phase qui peut être déterminée par étalonnage ou à l'aide des méthodes de calcul décrites dans l'IEC 62127-1:2022.

ULTRASONS – HYDROPHONES –

Partie 3: Propriétés des hydrophones pour les champs ultrasoniques

1 Domaine d'application

La présente partie de l'IEC 62127 spécifie les caractéristiques pertinentes des **hydrophones**.

Le présent document s'applique:

– aux **hydrophones** qui utilisent des capteurs piézoélectriques conçus pour mesurer les champs ultrasoniques à ondes par impulsions et entretenues générés par les appareils à ultrasons;
– aux **hydrophones** utilisés pour les mesurages réalisés dans l'eau;
– aux **hydrophones** avec ou sans préamplificateur associé.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition mentionnée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 62127-1, *Ultrasons – Hydrophones – Partie 1: Mesurage et caractérisation des champs ultrasoniques médicaux*

IEC 62127-2, *Ultrasons – Hydrophones – Partie 2: Étalonnage des champs ultrasoniques jusqu'à 40 MHz*

3 Termes, définitions et symboles

Pour les besoins du présent document, les termes et définitions de l'IEC 62127-1, de l'IEC 62127-2 ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
forme d'onde des impulsions acoustiques
forme d'onde temporelle de la **pression acoustique instantanée** en une position spécifiée d'un champ acoustique, présentée sur une période suffisamment longue pour inclure toutes les indications acoustiques significatives dans une impulsion, une salve d'impulsions ou un ou plusieurs cycles d'une onde entretenue

Note 1 à l'article: La forme d'onde temporelle est une représentation (par exemple, présentation par oscilloscope ou formule) de la **pression acoustique instantanée**.

[SOURCE: IEC 62127-1:2022, 3.1]

3.2
réponse directionnelle
description de la réponse d'un **hydrophone**, en fonction de la direction de propagation de l'onde sonore incidente plane, dans un plan spécifié qui passe par le **centre de référence** et à une fréquence spécifiée

Note 1 à l'article: Même si la **réponse directionnelle** est une fonction à valeur complexe, le module de la **réponse directionnelle** est généralement plus significatif et est couramment représenté sous forme graphique.

[SOURCE: IEC 60565:2006, 3.5, modifiée – Dans la définition, ", habituellement présentée sous forme de graphique," a été supprimé; "transducteur électroacoustique" a été remplacé par "hydrophone"; et "onde rayonnée ou incidente" a été remplacé par "onde sonore incidente plane".]

3.3
taille efficace de l'hydrophone
a_{h}
dimension d'un **hydrophone** de récepteur théorique qui comporte une fonction de **réponse directionnelle** prévue à angle d'ouverture égal à l'angle d'ouverture observé

Note 1 à l'article: D'une manière générale, la taille dépend de la fréquence. Pour consulter des données expérimentales représentatives, voir [1].

Note 2 à l'article: La **taille efficace de l'hydrophone** est exprimée en mètres (m).

Note 3 à l'article: Pour les hydrophones de géométrie circulaire, la **taille efficace de l'hydrophone** est un rayon.

Note 4 à l'article: Pour les hydrophones de géométrie rectangulaire, la **taille efficace de l'hydrophone** est la moitié de la valeur la plus élevée de la longueur ou de la largeur.

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

3.4
impédance de charge électrique
$\underline{Z}_{\mathrm{L}}$
impédance d'entrée électrique complexe (composée d'une partie réelle et d'une partie imaginaire) à laquelle le câble de sortie de l'hydrophone est ou est destiné à être connecté

Note 1 à l'article: L'**impédance de charge électrique** est exprimée en ohms (Ω).

[SOURCE: IEC 62127-1:2022, 3.22]

3.5
bout de câble
<**hydrophone** ou **ensemble d'hydrophones** équipé d'un câble de sortie intégré> se rapporte à l'extrémité du câble de sortie intégré

3.6
bout de câble
<**hydrophone** ou **ensemble d'hydrophones** non équipé d'un câble de sortie intégré> se rapporte au connecteur de sortie qui est solidement raccordé à l'**hydrophone** ou à l'**ensemble d'hydrophones** et non à un câble supplémentaire

3.7
sensibilité en charge en bout de câble
$\underline{M}_{\mathrm{L}}(f)$
<d'un **hydrophone** ou d'un **ensemble d'hydrophones**> quotient du signal tension-temps de transformée de Fourier d'un **hydrophone** $\mathcal{F}(u_{\mathrm{L}}(t))$ à l'extrémité d'un câble intégré ou d'un connecteur de sortie d'un **hydrophone** ou d'un **ensemble d'hydrophones**, lorsqu'il est connecté à une **impédance de charge électrique** spécifiée, par la **forme d'onde des impulsions acoustiques** de transformée de Fourier $\mathcal{F}(p(t))$ dans le champ libre non perturbé d'une onde plane dans la position du **centre de référence** de l'**hydrophone**, si l'**hydrophone** a été retiré

$$\underline{M}_{\mathrm{L}}(f)=\frac{\mathcal{F}\left(u_{\mathrm{L}}(t)\right)}{\mathcal{F}\left(p(t)\right)} \tag{1}$$

Note 1 à l'article: La **sensibilité en charge en bout de câble** est un paramètre à valeur complexe. Son module est exprimé en volts par pascal (V/Pa), son angle de phase est exprimé en degrés, et il représente la différence de phase entre la tension électrique et la pression acoustique.

3.8
sensibilité en circuit ouvert en bout de câble
$\underline{M}_{\mathrm{c}}(f)$
<d'un **hydrophone**> quotient du signal tension-temps en circuit ouvert de transformée de Fourier de l'**hydrophone** $\mathcal{F}(u_{\mathrm{c}}(t))$ à l'extrémité d'un câble intégré ou d'un connecteur de sortie d'un **hydrophone** par la **forme d'onde des impulsions acoustiques** de transformée de Fourier $\mathcal{F}(p(t))$ dans le champ libre non perturbé d'une onde plane dans la position du **centre de référence** de l'**hydrophone**, si l'**hydrophone** a été retiré

$$\underline{M}_{\mathrm{c}}(f)=\frac{\mathcal{F}\left(u_{\mathrm{c}}(t)\right)}{\mathcal{F}\left(p(t)\right)} \tag{2}$$

Note 1 à l'article: La **sensibilité en circuit ouvert en bout de câble** est un paramètre à valeur complexe. Son module est exprimé en volts par pascal (V/Pa), son angle de phase est exprimé en degrés, et il représente la différence de phase entre la tension électrique et la pression acoustique.

3.9
niveau de sensibilité en charge en bout de câble
$L_{M_{\mathrm{L}}}(f)$
<d'un **hydrophone** ou d'un **ensemble d'hydrophones**> vingt fois le logarithme décimal du quotient du module de la **sensibilité en charge en bout de câble** $|\underline{M}_{\mathrm{L}}(f)|$ par une sensibilité de référence M_{ref}

$$L_{M_{\mathrm{L}}}(f)=20\log_{10}\frac{\left|\underline{M}_{\mathrm{L}}(f)\right|}{M_{\mathrm{ref}}}\ \mathrm{dB} \tag{3}$$

Note 1 à l'article: Les valeurs couramment utilisées pour la sensibilité de référence M_{ref} sont 1 V/µPa ou 1 V/Pa.

Note 2 à l'article: Le **niveau de sensibilité en charge en bout de câble** est exprimé en décibels (dB).

3.10
champ libre
champ acoustique en milieu homogène et isotrope dans lequel les effets des limites sont négligeables

[SOURCE: IEC 60565:2006, 3.13]

3.11
taille géométrique de l'hydrophone
taille géométrique d'un élément actif de l'hydrophone
a_g
taille définie par les extensions latérales de l'élément actif d'un **hydrophone**

Note 1 à l'article: La **taille géométrique de l'hydrophone** est exprimée en mètres (m).

Note 2 à l'article: Pour les **hydrophones** de géométrie circulaire, la **taille géométrique de l'hydrophone** est un rayon.

Note 3 à l'article: Pour les hydrophones de géométrie rectangulaire, la **taille géométrique de l'hydrophone** est la moitié de la valeur la plus élevée de la longueur ou de la largeur.

3.12
hydrophone
transducteur qui produit des signaux électriques en réponse aux variations de pression dans l'eau

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

3.13
ensemble d'hydrophones
combinaison d'un **hydrophone** et d'un **préamplificateur d'hydrophone**

3.14
axe de l'hydrophone
axe de symétrie nominal de l'élément actif de l'**hydrophone**

Note 1 à l'article: Sauf indication contraire (explicite et quantitative) du fabricant, il est admis pour les besoins du présent document qu'il est donné par l'axe de symétrie géométrique apparent de l'**hydrophone**.

3.15
préamplificateur d'hydrophone
dispositif électronique actif connecté ou qui doit être connecté à un **hydrophone** particulier et qui permet de réduire son impédance de sortie

Note 1 à l'article: Le **préamplificateur d'hydrophone** exige une ou plusieurs tensions d'alimentation.

Note 2 à l'article: Le **préamplificateur d'hydrophone** peut avoir un facteur de transmission de la tension directe inférieur à un. Autrement dit, il peut ne pas forcément être un amplificateur de tension stricto sensu.

3.16
centre de référence
point situé sur un **hydrophone** ou au voisinage de celui-ci autour duquel sa sensibilité de réception acoustique est définie

Note 1 à l'article: Sauf indication contraire (explicite et quantitative) du fabricant, il est admis pour les besoins du présent document qu'il est donné par le centre géométrique de la surface frontale de l'élément actif de l'**hydrophone**.

[SOURCE: IEC 60565:2006, 3.25, modifiée – Dans la définition, "transducteur" a été remplacé par "hydrophone" et "réponses de transmission" n'a pas été repris. La note a été remplacée.]

3.17
incertitude
paramètre associé au résultat d'un mesurage, qui caractérise la dispersion des valeurs qui peuvent être raisonnablement attribuées au mesurande

Note 1 à l'article: Voir le 2.2.3 du Guide 98-3:2008 de l'ISO/IEC [2].

[SOURCE: IEC 62127-1:2022, 3.92]

4 Liste des symboles

a_{g}	**taille géométrique de l'hydrophone**
a_{h}	**taille efficace de l'hydrophone**
c	vitesse du son dans un milieu
D_{H}	fonction modèle utilisée lors de la détermination de la **taille efficace de l'hydrophone** à partir de la **réponse directionnelle** mesurée d'un **hydrophone**
f	fréquence
k	nombre d'onde, égal à $2\pi/\lambda$
$L_{M_{\mathrm{L}}}(f)$	**niveau de sensibilité en charge en bout de câble**
$\underline{M}$	symbole général de la sensibilité complexe de l'**hydrophone**, $M = \lvert\underline{M}\rvert$ étant son module et arg($\underline{M}$) son argument (égal à l'angle de phase)
$\underline{M}_{\mathrm{c}}$	**sensibilité en circuit ouvert en bout de câble**
$\underline{M}_{\mathrm{L}}$	**sensibilité en charge en bout de câble**
$\underline{Z}_{\mathrm{h}}$	impédance de sortie électrique complexe d'un **hydrophone** ou d'un **ensemble d'hydrophones**
$\underline{Z}_{\mathrm{L}}$	**impédance de charge électrique**
θ	angle d'incidence d'une onde ultrasonique par rapport à l'**axe de l'hydrophone**

5 Caractéristiques des hydrophones

5.1 Généralités

Pour caractériser de manière exhaustive les performances d'un hydrophone dans la plage de fréquences du présent document, les informations suivantes sont exigées. Des exemples d'informations relatives aux caractéristiques de l'hydrophone sont fournis à l'Annexe A.

NOTE Les méthodes de détermination sont traitées dans l'IEC 62127-2.

5.2 Informations de base

Les informations suivantes doivent être fournies de manière concise:

– les principes physiques de base du processus de transduction, le type de matériau du capteur considéré, la forme et les dimensions géométriques (diamètre, épaisseur) de l'élément actif de l'**hydrophone** et le diamètre de l'aiguille dans le cas d'un **hydrophone** à aiguille;
– la configuration et la conception de l'**hydrophone**;
– une indication précisant si un préamplificateur est associé ou non à l'**hydrophone**; si le préamplificateur peut être déconnecté de l'**hydrophone**, des informations claires doivent préciser le type de préamplificateur correspondant au type d'**hydrophone**;
– la direction nominale de l'incidence ultrasonique par rapport à l'**hydrophone**.

NOTE Ce dernier point est important, car l'ouvrage [3][1] a démontré que même pour les **hydrophones** à membrane, la réponse peut varier en cas d'inversion de la direction de propagation ultrasonique par rapport à l'**hydrophone**.

Il convient de fournir les informations suivantes de manière concise:

– les dimensions latérales et l'épaisseur de l'élément actif de l'**hydrophone**;
– la fréquence de la résonance d'épaisseur fondamentale de l'élément actif de l'**hydrophone**;
– la taille et la masse de l'**hydrophone**;
– le modèle de **réponse directionnelle** recommandé (voir le 5.6.2) pour l'**hydrophone**;
– dans le cas d'un **hydrophone** à membrane, la réflexion acoustique et le facteur de transmission (préférentiellement en fonction de la fréquence);
– des informations relatives à l'affaiblissement du préamplificateur aux basses fréquences en dehors de la plage d'étalonnage de l'hydrophone, le cas échéant, afin d'assurer une extrapolation appropriée des données d'étalonnage conformément à l'IEC 62127-1:2022.

Note générale relative au 5.3 et au 5.4: si des informations de phase sont disponibles, il convient de définir l'angle de phase (qui est égal à l'argument de la sensibilité complexe de l'**hydrophone**) en plus de la sensibilité (qui est égale au module de la sensibilité complexe de l'**hydrophone**), ainsi que la dépendance de l'angle de phase vis-à-vis de la fréquence en plus de la dépendance de la sensibilité vis-à-vis de la fréquence.

5.3 Sensibilité

Le module de la sensibilité en **bout de câble** de l'**hydrophone** ou de l'**ensemble d'hydrophones** doit être exprimé en volts par pascal (V/Pa) ou en sous-multiples décimaux, ou sous la forme d'un niveau logarithmique décibels (dB) en référence à la valeur de sensibilité indiquée.

NOTE 1 Pour la définition du **niveau de sensibilité en charge en bout de câble**, voir le 3.9.

Si un préamplificateur contribue à la valeur de sensibilité donnée, cela doit être indiqué.

Il doit être précisé si la valeur de sensibilité donnée s'entend comme la **sensibilité en circuit ouvert en bout de câble** ou comme la **sensibilité en charge en bout de câble**. Dans ce dernier cas, les conditions de charge électrique correspondantes, c'est-à-dire l'**impédance de charge électrique**, doivent être indiquées afin d'obtenir la sensibilité indiquée.

L'**incertitude** de la sensibilité indiquée doit être donnée.

L'intervalle de fréquence sur lequel est donnée la sensibilité et sur lequel s'applique l'**incertitude** doit être indiqué. Pour les besoins du présent document, les valeurs de sensibilité et d'**incertitude** peuvent être données séparément pour plusieurs intervalles de fréquence.

Les méthodes qui permettent de déterminer la sensibilité et son **incertitude** doivent être décrites.

La dépendance de la sensibilité vis-à-vis de la température doit être donnée. La sensibilité de l'**hydrophone** doit être indiquée en fonction de la température de l'eau, au moins dans la plage de températures comprises entre 19 °C et 25 °C, ou la température de l'eau particulière à laquelle se rapporte la sensibilité indiquée doit être donnée avec le coefficient de température de la sensibilité.

1 Les chiffres entre crochets renvoient à la Bibliographie

Une période d'étalonnage recommandée doit être indiquée dans les instructions d'utilisation. Cette recommandation s'applique, sauf indication contraire dans les normes d'application spécifiques du dispositif.

NOTE 2 Une période d'étalonnage d'une année est appropriée dans la plupart des cas.

Le **centre de référence** doit être indiqué si la sensibilité n'est pas liée au centre géométrique de la surface frontale de l'élément actif de l'**hydrophone**.

NOTE 3 Cela est particulièrement important pour les aspects liés à la phase.

La direction de l'incidence acoustique doit être indiquée si la sensibilité n'est pas liée à une incidence dans la direction de l'**axe de l'hydrophone**.

5.4 Réponse en fréquence

5.4.1 Bande de fréquences indiquée

La bande de fréquences demandée pour l'**hydrophone** ou l'**ensemble d'hydrophones** doit être précisée en indiquant les limites de fréquence inférieure et supérieure. Le module de la sensibilité en **bout de câble** de l'**hydrophone** ou de l'**ensemble d'hydrophones** doit être constant sur toute la bande de fréquences indiquée, avec une tolérance qui doit également être précisée.

5.4.2 Dépendance vis-à-vis de la fréquence

Le module de la sensibilité ou le niveau de sensibilité en **bout de câble** de l'**hydrophone** ou de l'**ensemble d'hydrophones** en fonction de la fréquence doit être indiqué de manière graphique ou sous la forme d'une liste de valeurs et sur une plage de fréquences qui contient au moins la bande de fréquences demandée au 5.4.1. S'il est donné sous la forme d'une liste de valeurs ou de points discrets sur un graphique, il convient que l'écart de fréquence entre deux points adjacents soit suffisamment faible pour que tous les détails importants de la dépendance vis-à-vis de la fréquence soient représentés et que le niveau de sensibilité ne varie pas de plus de ±1 dB entre les points adjacents.

La réponse en fréquence peut être donnée sous la forme de valeurs de sensibilité absolue ou dans une représentation en valeur relative, en référence à la sensibilité absolue de l'**hydrophone** ou de l'**ensemble d'hydrophones** à une fréquence donnée. Dans le cas d'une représentation en valeur relative, la sensibilité de référence et la fréquence à laquelle elle s'applique doivent être indiquées.

La phase de la sensibilité en **bout de câble** peut être donnée en fonction de la fréquence, sous forme graphique ou sous la forme d'une liste de valeurs.

La déclaration de la réponse en fréquence doit faire référence aux mêmes conditions (c'est-à-dire sortie en charge ou en circuit ouvert de l'**hydrophone** ou de l'**ensemble d'hydrophones**) que la déclaration de la sensibilité conformément au 5.3.

Toute différence entre l'**incertitude** des valeurs de sensibilité dans la représentation de la réponse en fréquence et l'**incertitude** évaluée au 5.3 doit être indiquée clairement, et la nouvelle **incertitude** ou l'**incertitude** supplémentaire doit être donnée.

Si la réponse en fréquence est donnée sous la forme d'une liste de valeurs de sensibilité absolue (en **bout de câble**, en charge ou en circuit ouvert), la déclaration de la sensibilité conformément au 5.3 peut être ignorée.

NOTE 1 La réponse en fréquence peut dépendre des conditions de charge électrique.

NOTE 2 Si, dans une application pratique, l'**hydrophone** ou l'**ensemble d'hydrophones** est utilisé, par la suite, avec des composants électroniques comme un amplificateur, un oscilloscope, etc., la réponse en fréquence de ces composants supplémentaires aura bien entendu également une incidence sur la réponse en fréquence de l'ensemble du système.

5.5 Réponse directionnelle

5.5.1 Généralités

La réponse directionnelle et les grandeurs déterminées à partir de celle-ci ont fait l'objet de nombreuses modifications par rapport à la première édition de l'IEC 62127-3. Les détails de la justification de ces modifications peuvent être consultés à l'Annexe B.

5.5.2 Détermination de la réponse directionnelle

La **réponse directionnelle** de l'**hydrophone** doit être indiquée pour au moins trois fréquences, la plus basse fréquence et la plus haute fréquence étant aussi éloignées que possible l'une de l'autre.

– Il convient que la plus basse fréquence à laquelle a été déterminée la **réponse directionnelle** de l'**hydrophone** corresponde à la limite inférieure de la bande de fréquences demandée au 5.4.1. Dans le cas contraire, la ou les raisons de la variation doivent être indiquées.

– Il convient que la plus haute fréquence à laquelle a été déterminée la **réponse directionnelle** de l'**hydrophone** corresponde à la limite supérieure de la bande de fréquences demandée au 5.4.1. Dans le cas contraire, la ou les raisons de la variation doivent être indiquées.

  NOTE La détermination expérimentale de la **réponse directionnelle** devient plus complexe à mesure que la fréquence augmente. Par conséquent, la plus haute fréquence à laquelle il est pratique de déterminer la **réponse directionnelle** de l'**hydrophone** peut être inférieure à la bande de fréquences supérieures demandée au 5.4.1. Cependant, la **taille efficace de l'hydrophone** devient asymptotique à mesure que la fréquence augmente. Par conséquent, la variation de la **taille efficace de l'hydrophone** est susceptible d'être négligeable aux fréquences supérieures à la plus haute fréquence à laquelle a été évaluée la **réponse directionnelle**.

– La fréquence médiane située à ±15 % de la moyenne géométrique des fréquences inférieure et supérieure à laquelle a été déterminée la **réponse directionnelle** de l'**hydrophone** est la troisième fréquence à laquelle la réponse directionnelle doit être indiquée. Dans le cas contraire, la ou les raisons de la variation doivent être indiquées.

– Si la résonance d'épaisseur fondamentale de l'**hydrophone** se situe dans la plage des fréquences inférieure et supérieure indiquée dans le présent 5.5.2, la **réponse directionnelle** à cette fréquence doit également être indiquée. Dans le cas contraire, la ou les raisons de la variation doivent être indiquées.

Il convient de mesurer la **réponse directionnelle** par rotation de l'**hydrophone** autour d'un axe qui passe par le **centre de référence** et qui est perpendiculaire à l'**axe de l'hydrophone**, compris au moins entre −35° et +35° (avec l'**axe de l'hydrophone** en référence) ou au moins entre la valeur minimale de gauche et la valeur minimale de droite, si cette portée angulaire est mois importante. Si cette méthode est utilisée, elle doit être appliquée deux fois, à savoir autour de deux axes de rotation perpendiculaires. Si, dans le plan perpendiculaire à son axe, un **hydrophone** présente une direction distincte donnée (celle des fils électriques dans le cas d'un **hydrophone** à membrane, par exemple), il convient d'orienter les axes de rotation dans cette direction et perpendiculairement à celle-ci. Si l'élément actif n'est pas circulaire, l'un des axes de rotation doit suivre la direction de la plus grande dimension. Les directions des axes de rotation doivent être identifiées par marquage sur l'**hydrophone** ou précisées dans la documentation d'accompagnement.

L'incrément angulaire doit être choisi de manière à s'assurer que la variation entre les points adjacents de la **réponse directionnelle** ne dépasse pas 1 dB.

La **réponse directionnelle** doit être mesurée dans un champ ultrasonique d'onde quasi plane.