BRITISH STANDARD

BS EN 60565:2007

Underwater acoustics — Hydrophones — Calibration in the frequency range 0,01 Hz to 1 MHz

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British Standards

National foreword

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(IEC 60565:2006)

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Hydrophones -
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de 0,01 Hz à 1 MHz
(CEI 60565:2006)

Wasserschall -
Hydrophone -
Kalibrierung im Frequenzbereich
von 0,01 Hz bis 1 MHz
(IEC 60565:2006)

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Foreword

The text of document 87/357/FDIS, future edition 2 of IEC 60565, prepared by IEC TC 87, Ultrasonics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60565 on 2006-12-01.

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Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60565:2006 was approved by CENELEC as a European Standard without any modification.

CONTENTS

UNDERWATER ACOUSTICS – HYDROPHONES – CALIBRATION IN THE FREQUENCY RANGE 0,01 Hz TO 1 MHz

1 Scope

This International Standard specifies methods for calibration of hydrophones or reversible transducers when used as a hydrophone, particularly in the frequency range from 0,01 Hz to 1 MHz. Rules for the presentation of the calibration data are established.

2 Normative references

The following referenced data are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-801, *International Electrotechnical Vocabulary - Chapter 801: Acoustics and electroacoustics*

IEC 60500:1974, *IEC Standard hydrophone*

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

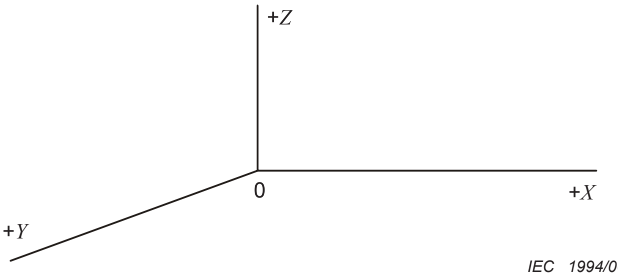
3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
angular deviation loss
sensitivity level of the transducer on the principal axis minus the sensitivity level of the transducer for a specified direction

[IEV 801-25-69]

3.2
co-ordinate system
system used to designate the directivity pattern of the transducer



IEC 1994/06

Figure 1 – Left-hand co-ordinate system

Line transducer: central line of symmetry along the Z-axis;

Dipole transducer: both components equidistant from the origin, along the +Z and –Z axis;

Piston transducer: piston plane in ZOY-plane; principal axis along X-axis.

NOTE 1 The terms ’horizontal directivity pattern’ and ’vertical directivity pattern’ are often used for representation of directivity in the XY- and XZ- (or YZ-) planes respectively.

NOTE 2 See Annex A, [1][1], [2].

3.3
coupler

apparatus comprising a rigid fluid-filled chamber of small dimensions into which transducers and hydrophones can be inserted

3.4
diffraction factor

ratio of the average pressure over the part of the hydrophone designed to receive sound to the free-field sound pressure that would exist at the reference centre of the hydrophone

3.5
directional response

description, generally presented graphically, of the response of an electro-acoustic transducer, as a function of the direction of propagation of the radiated or incident sound in a specified plane through the reference centre and at a specified frequency

NOTE See Annex A.

3.6
dynamic range

ratio of the maximum free field sound pressure that produces an undistorted hydrophone output to the equivalent noise pressure at the hydrophone

3.7
electrical impedance of a transducer

complex ratio of the instantaneous voltage applied across the electrical terminals of a transducer at a given frequency, to the resulting instantaneous current

NOTE 1 The unit is the ohm, Ω.

NOTE 2 Because the electrical impedance depends on the field conditions, the hydrostatic pressure, water temperature and the length of the cable attached to the transducer, these parameters, as well as the frequency and the electrical terminals where the electrical impedance is measured should be specified.

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[1] Numbers in square brackets refer to the bibliography

3.8

electrical terminals of a reciprocal transducer

terminals across which the open circuit hydrophone voltage , as well as the projector current are measured

NOTE If the transducer is immersed in water, the electrical terminal with the lowest electrical impedance with respect to water is called the ’low terminal’. Consequently, the other electrical terminal is called the ‘high terminal’.

3.9

electrical transfer impedance magnitude

magnitude of the electrical transfer impedance of a transducer pair

NOTE The unit is the ohm, Ω.

3.10

electrical transfer impedance of a transducer pair

complex ratio of the open circuit instantaneous voltage U_{H} across the hydrophone electrical terminals to the instantaneous current I_{P} through the projector, if projector and hydrophone are mounted in a free field with their principal axes in line and directed towards each other

NOTE 1 $$Z_{\mathrm{PH}} = \frac{U_{\mathrm{H}}}{I_{\mathrm{P}}} \qquad (1)$$

NOTE 2 The unit is the ohm, Ω.

NOTE 3 The electrical transfer impedance is a complex quantity. It has both real and imaginary components and can be represented as a magnitude $|Z_{\mathrm{PH}}|$ times a phase term $\exp(j\varphi)$, where φ is the phase angle between the real and imaginary impedance components.

NOTE 4 The definition of principal axis is given in 3.23.

NOTE 5 See 7.5.

3.11

equivalent noise pressure

sound pressure applied at the hydrophone to cause a voltage at the hydrophone electrical terminals, in the absence of noise, that is equal to the noise voltage present at the same electrical terminals when the sound pressure is absent

NOTE When the equivalent noise pressure cannot be measured, it can be calculated from the equivalent series resistance [2].

3.12

far field

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

NOTE 1 In the far field, the sound pressure appears to be spherically divergent from a point on or near the radiating surface. Hence, the pressure produced by the sound source is inversely proportional to the distance from that source.

NOTE 2 For all practical calibrations, the separation distance between the sound source and the point where the pressure is measured is sufficiently large that the sound pressure is measured in the far field of the source.

3.13

free field

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

3.14
free-field sensitivity level
twenty times the logarithm to the base 10 of the ratio of the free-field sensitivity M_f to a reference sensitivity M_ref

NOTE 1 The unit is the decibel, dB.

NOTE 2 M_ref is equal to 1 V·µPa^{-1}.

NOTE 3 The use of units differing by a factor 10 to the power of n, (n being a positive or negative whole number) is allowed in accordance with the general rules for the SI system. In such cases, the value of M_ref is specially indicated.

3.15
free-field sensitivity of a hydrophone
ratio of the open circuit voltage of the hydrophone to the sound pressure in the undisturbed free field in the position of the reference centre of the hydrophone if the hydrophone were removed

NOTE 1 The unit is the volt per pascal, V·Pa^{-1}.

NOTE 2 The pressure is sinusoidal.

NOTE 3 The term 'response' is sometimes used instead of 'sensitivity'.

3.16
hydrophone
transducer that produces electric signals in response to water borne acoustic signals

NOTE Most hydrophones are reversible and satisfy the principle of reciprocity. Consequently, they may operate as projectors, unless they are permanently equipped with a preamplifier.

3.17
measurement uncertainty
range of values surrounding a measured value that has a specified probability of containing the correct value for the quantity being measured

NOTE Uncertainties given in this standard will represent expended uncertainty and be identified with 95 % confidence limits. Components of uncertainty include Type A, those that are evaluated by statistical methods and Type B, those that are evaluated by other means [3], see Annex D.

3.18
omnidirectionality
transducer response which shows variations smaller than a given limit as the direction is changed

NOTE Omnidirectionality in a two-dimensional space can occur in one plane only, while in three dimensions a transducer can be omnidirectional in all planes through the reference centre.

3.19
open-circuit voltage at hydrophone
voltage appearing at the electrical terminals of a hydrophone when no current passes through the terminals

NOTE 1 The unit is the volt, V.

NOTE 2 Throughout this standard, all voltages, currents and sound pressures are root mean square quantities, unless otherwise stated.

3.20
pistonphone
apparatus having a rigid piston which can be given a reciprocating motion of a known frequency and amplitude, so permitting the establishment of a known sound pressure in a closed chamber of small dimensions

NOTE The largest dimension of the enclosed space should be sufficiently small compared with the wavelength of the sound in the acoustic medium. See Clause 13.

3.21
pressure sensitivity level

twenty times the logarithm to the base 10 of the ratio of the pressure sensitivity M_{p} to a reference sensitivity of M_{ref}

NOTE 1 The unit is the decibel, dB.

NOTE 2 See 3.10, Notes 3 and 4.

3.22
pressure sensitivity of a hydrophone

ratio of the output voltage to the actual sound pressure existing over the region of the hydrophone designed to receive sound

NOTE 1 See 3.15, NOTES 2 and 3.

NOTE 2 The unit is the volt per pascal, $\mathrm{V{\cdot}Pa^{-1}}$

3.23
principal axis

reference direction serving as an origin for angular co-ordinates used in describing the directional characteristics of the transducer

NOTE 1 Generally, the axis of structural symmetry or the direction of maximum response is chosen for the principal axis.

NOTE 2 The direction of maximum response may vary with the frequency of the sound.

3.24
reciprocal transducer

linear, passive, reversible transducer

NOTE An example of a non-reciprocal transducer is one that mixes a magnetic field device with an electric field device.

3.25
reference centre

point on or near a transducer about which its acoustic receiving sensitivity and transmitting responses are defined

NOTE Generally, the reference centre should be chosen to be at or near the centre of the active portion of the transducer. This often corresponds to the geometric centre of the transducer. For example, the reference centre for a transducer utilizing a piezoelectric ceramic spherical shell should be located at the centre of the sphere. The reference centre of a piezoelectric spherical cap should be located on the axis of symmetry between the centre of curvature of the cap and the geometric centre of the cap. It should be located closer to the geometric centre of the cap for smaller cap angles. In the limiting case of a piston transducer, the reference centre should be located at the centre of the radiating piston face. This choice tends to minimize the measurement uncertainty introduced by performing calibrations at separation distances less than that required to achieve far-field conditions. (See 3.12).

3.26
reversible transducer

transducer capable of acting as a projector as well as a hydrophone

3.27
transmitting current response level

twenty times the logarithm to the base 10 of the ratio of the transmitting response S to a reference response S_{ref}

NOTE 1 The unit is the decibel, dB.

NOTE 2 S_{ref} is equal to 1 $\mu\mathrm{Pa{\cdot}m{\cdot}A^{-1}}$.

3.28
transmitting response to current of a projector

ratio of the sound pressure at a reference distance from the reference centre of a projector (at a given frequency and in a specified direction) multiplied by the reference distance, to the current flowing through the electrical terminal.

NOTE 1 Reference distance is 1 m.

NOTE 2 The unit is the pascal metre per ampere, $Pa \cdot m \cdot A^{-1}$.

3.29
transmitting response to voltage of a projector

ratio of the sound pressure at a reference distance from the reference centre of a projector (at a given frequency and in a specified direction), multiplied by the reference distance, to the voltage across the electrical terminals

NOTE 1 Reference distance is 1 m.

NOTE 2 The unit is the pascal metre per volt, $Pa \cdot m \cdot V^{-1}$.

3.30
transmitting voltage response level

twenty times the logarithm to the base 10 of the ratio of the transmitting response S_V to a reference response $S_{V,\,\mathrm{ref}}$

NOTE 1 The unit is the decibel, dB.

NOTE 2 $S_{\mathrm{V,\,ref}}$ is equal to 1 μPa·m·V-1.

3.31
point transducer

transducer which is omnidirectional in all planes and may have its axis in any direction

3.32
line transducer

transducer which is omnidirectional in one plane and may have its axis in any direction within that plane

3.33
dipole transducer

transducer which is bidirectional and has two axes in opposite directions

3.34
flat piston transducer

transducer which is unidirectional and has one axis, generally perpendicular to the piston surface

3.35
unidirectional transducer

transducer which is responsive predominately to sound radiated or incident within a solid angle not greater than one hemisphere

NOTE See [4] to [7].

3.36
small chamber transmitting response to current of a transducer

ratio of the acoustical pressure (assumed uniform) in a small chamber to the current flowing through the electrical terminals of a transducer inside the chamber at a given frequency

NOTE The unit is the Pascal per ampere, $Pa \cdot A^{-1}$.

3.37
projector
electro-acoustic transducer that converts electric signals into sound signals propagating in water

3.38
vibrating column
apparatus in which a column of water in a vertically placed cylindrical container is set in vibration, causing a depth-dependent sound pressure in the water column

NOTE 1 The length of the column should be sufficiently small compared with the wavelength of the sound in the water. The cross-sectional dimensions of the column should be small compared with its length.

NOTE 2 See Clause 14.

4 Symbols and abbreviated terms

Symbol	Meaning
A	Effective sensitive area of transducer
a	Linear dimension of transducer
B	Flux density of magnetic field through transducer coil
C	Capacitance
C_c	Acoustic compliance of chamber walls
C_f	Acoustic compliance of fluid volume in chamber
C_{mt}	Mechanical compliance of chamber
C_t	Acoustic compliance of chamber
C_w	Acoustic compliance of water volume in chamber
c	Speed of sound in water
c_f	Speed of sound in a fluid
D	Mean diameter of cylindrical shell
D_i	Directivity index
d	Distance between projector and hydrophone
d_{31}	Piezoelectric modulus
$\mathrm{d}S$	Differential area on a sphere
E	Young’s modulus
f	Frequency
g	Acceleration due to gravity
h	Height of water column
I	Current
I_P	Current through projector
I_T	Current through transducer

I_c	Compensation current through null projector
K	Characteristic constant of piezoelectric null transducer
K_f^2	Correction factor
K_0	Increasing factor
ℓ	Length of column
l	Width of tank
M_f	Free-field sensitivity
M_H	Free-field sensitivity of hydrophone
M_M	Pressure sensitivity of microphone
M_T	Free-field sensitivity of transducer
M_P	Free-field sensitivity of projector
M_p	Pressure sensitivity
m	Mass of water inside chamber
p	Sound pressure
P	Projector
Q	Quality factor
R	Resistance
R_θ	Directivity factor
r	Radius of transducer shell
S	Transmitting response to current
S_H	Transmitting response to current of a hydrophone when used as a projector
S_P	Transmitting response to current of a projector
S_T	Transmitting response to current of a transducer
S_V	Transmitting response to voltage of a projector
t	Thickness of cylindrical shell
U	Voltage
U_c	Compensating voltage at null projector
U_H	Open circuit voltage at hydrophone
U_M	Open circuit voltage at microphone
U_P	Transmitting voltage at projector
U_T	Transmitting voltage at transducer
U_PH	Open circuit voltage at hydrophone, from a projector as sound source
U_TH	Open circuit voltage at hydrophone, from a transducer as sound source

U_{PT}	Open circuit voltage at transducer, from a projector as sound source
V	Water volume, chamber volume
V_{D}	Volume displacement
W	Bandwidth
x	Displacement of null transducer, vibration amplitude
Z	Impedance
Z_{eq}	A function of transfer impedances having the dimension of impedance
Z_{PH}	Electrical transfer impedance of projector and hydrophone
Z_{TH}	Electrical transfer impedance of transducer and hydrophone
Z_{PT}	Electrical transfer impedance of transducer and projector
γ	Ratio of specific heats
θ	Vertical angle
λ	Wavelength of sound in water
λ_{f}	Wavelength of sound in a fluid
ν	Rotational velocity
ρ	Density of water
ρ_{f}	Density of fluid
σ	Poisson’s modulus
τ	Pulse duration
φ	Azimuth angle
ω	Angular frequency $= 2\pi f$
S_T	Small chamber transmitting response to current of a transducer

5 Procedures for calibrations

5.1 Principles

a) Calibration without a standard transducer

1) Reciprocity calibration:

Calibration is based upon the reciprocity principle, in which at least one transducer is a reciprocal transducer.

2) Physical calibration:

The sound pressure at the hydrophone is calculated from the measurement of physical parameters such as displacement, velocity or acceleration, medium compliance, etc. (e.g.: null transducer, pistonphone, vibrating column, etc.).

b) Calibration with a standard transducer:

A hydrophone or a projector is calibrated by comparison with a calibrated standard transducer.

NOTE In the latter case, the calibrated projector can be used to calibrate another hydrophone.

5.2 Field limitations

Calibration shall be carried out by one of the following methods.

a) Free-field calibration in accordance with Clauses 8 or 9.

NOTE The boundaries of the sound field are such that calibration is possible in free field conditions (see 3.13).

b) Small chamber calibration in accordance with Clauses 10, 11, 12 or 13.

NOTE In this case, the sound field is restricted within a small space of which the largest dimension is sufficiently less than one wavelength of the sound (see 11.4 and 11.5).

5.3 Schematic survey of procedures

Calibration shall be carried out by one of the following methods, depending on the different principles and on the limitations in the sound field and in the frequency range.

a) Free-field reciprocity calibration in accordance with Clause 8 for calibration without a standard transducer in a free field, between 1 kHz and 1 MHz.

b) Free-field calibration by comparison in accordance with Clause 9 for calibration with a standard transducer in a free field, between 10 Hz and 1 MHz.

c) Calibration by hydrostatic excitation in accordance with Clause 10 for physical calibration without a standard transducer in a small chamber, between 0,01 Hz and 2 Hz.

d) Calibration by piezoelectric compensation in accordance with Clause 11 for physical calibration without a standard transducer in a small closed chamber, between 1,0 Hz and 5 kHz.

e) Acoustical coupler reciprocity calibration in accordance with Clause 12 for calibration without a standard transducer in a small closed chamber, between 0,1 Hz and 5 kHz.

f) Calibration with a pistonphone in accordance with Clause 13 for physical calibration with and without a standard transducer in a small chamber, from a few hertz to several hundred hertz.

g) Calibration with a vibrating column in accordance with Clause 14 for physical calibration without a standard transducer in a small chamber, between 10 Hz and 1 kHz.

5.4 Reporting of results

Any calibration is only valid on the date of calibration and for the environmental conditions which existed during the calibration. When the result of the calibration of a hydrophone is reported, the environmental conditions that pertain to that calibration shall be stated, including all those conditions that may influence the sensitivity of the device [8], [9], [10], [11] and [12].

NOTE 1 Conditions to be reported may include:

- date of the evaluation;
- water temperature;
- depth of immersion (or applied hydrostatic pressure);
- type of mount or rigging used;
- length of soaking time and any wetting procedure adopted;
- orientation of the transducer about any axis or alignment mark and whether the alignment was done manually or acoustically;
- maximum acoustic pressure experienced by the hydrophone;
- any assumptions made about the device under test (e.g., the position of the reference centre).

NOTE 2 If use is made of a calibrated hydrophone in an environment significantly different then that which existed during calibration, the user may need to increase his assessment of measurement uncertainties to account for the change in environment.

5.5 Recalibration periods

Reference hydrophones used for absolute measurements shall be calibrated periodically in order to maintain a valid calibration status. An appropriate period between calibrations shall be chosen after consideration of the use that is made of the hydrophone and the likelihood for damage to the device.

NOTE For reference hydrophones, which are used purely for calibration purposes, an annual recalibration calibration may be appropriate (see IEC 60866). Where hydrophones are used in the field and potentially may be subjected to abuse, calibrations may be required at shorter intervals.

5.6 Temperature and pressure considerations for calibration

NOTE 1 The electroacoustic properties of transducers tend to vary with both ambient temperature and hydrostatic pressure (depth) [9], [10].

Where the sensitivity of a transducer is required for specific conditions of water temperature and hydrostatic pressure (water depth), the transducer shall either:

a) be calibrated under the same conditions of temperature and pressure that it will be used; or

b) corrections to transducer sensitivity and response values shall be made based on earlier calibrations or validated analytical models.

6 Preparation of transducers

6.1 Wetting

To make sure that the transducer is wetted properly by the water without trapping an air film or bubbles on its surface, a wetting agent shall be applied to the whole transducer surface. No dry patches shall be visible on the transducer when it is immersed and then removed from the water [11].

6.2 Hydrophone support

The supporting mount for a hydrophone shall be chosen to cause minimal influence on the measured sensitivity. If the mount influences the measured sensitivity, the hydrophone shall be calibrated in the same mount that will be used for measurements made with the hydrophone in the field. Where the hydrophone is thought to be sensitive to the type of support/mount, a description of the mounting arrangement shall be stated with the results.

NOTE 1 Some hydrophones are more susceptible than others to the influence of the method of mounting.

NOTE 2 Care should also be taken to minimize the amount of structure borne noise which may be picked up.

6.3 Influence of cable

If the cable to the hydrophone needs to be lengthened for the purposes of the calibration, then the electrical impedance of the extension cable shall be measured separately in order to calculate the influence of electrical loading.

NOTE A description of how to account for the influence of electrical loading is given in Annex B. See also 7.3.

7 Electrical measurements

7.1 Signal type

The signal used for the calibration shall be either sinusoidal (continuous wave) or pulsed sine wave (gated tone burst). A sufficient number of frequencies shall be chosen to ensure that the hydrophone performance is well characterized over the desired frequency range.

7.2 Earthing

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

7.3 Measurement of hydrophone output voltage

7.3.1 General

The open-circuit voltage of the hydrophone shall be measured at the end of the hydrophone cable. The electrical terminals selected shall be specified (see 3.8).

For a continuous wave signal, the measurement shall be done using a voltmeter of high electrical input impedance. However, for tone-burst signals, the hydrophone voltage waveform shall be digitized, for example using a digitizing oscilloscope or a computer-based analogue-to-digital converter.

Where an amplifier, attenuator or filter are used in combination with the voltmeter or digitizer to form a measuring channel, these elements shall be calibrated, unless the same measuring channel is also used for the measurement of projector current (see 7.4).

7.3.2 Electrical loading by measuring instrument

During the measurements, the hydrophone shall be connected to a high electrical input-impedance measuring instrument (amplifier, voltmeter, oscilloscope or digitizer) such that the electrical input impedance is much larger than the electrical impedance of the hydrophone (ideally, more than 100 times larger). When measuring the phase angle of the hydrophone output voltage, the electrical input impedance of the measuring instrument shall be more than 1 000 times the electrical impedance of the hydrophone. Where the electrical impedance of the hydrophone is high (for example for a small piezoelectric hydrophone of low capacitance), consideration shall be given to the electrical loading of the hydrophone by the measuring instrument. In such cases, electrical loading corrections shall be applied to the measured voltage to obtain the open-circuit voltage.

NOTE 1 The corrections may be calculated using the procedure given in Annex B.

NOTE 2 If the same electrical load is used throughout the calibration for a particular hydrophone, the corrections may be applied to the sensitivity rather than to the individual measured voltages.

7.3.3 Electrical loading by extension cables

If extension cable is attached to the hydrophone, this cable will electrically load the hydrophone and corrections shall be applied to obtain the open-circuit end-of-cable hydrophone voltage. Where the cable and hydrophone appear electrically to be purely capacitances (this is generally true for a cable and is true for a hydrophone in the frequency range well below resonance), a correction shall be derived from the capacitances of the hydrophone and cable. Where the electrical impedance of the hydrophone is not purely capacitance for example, at frequencies close to resonance, the complex electrical impedance shall be used to calculate the loading correction.

NOTE 1 Guidance on both the above cases is given in Annex B.

NOTE 2 If the same extension cable is used throughout the calibration for a particular hydrophone, the corrections may be applied to the sensitivity rather than to the individual measured voltages.

7.3.4 Noise

The signal to noise ratio shall be sufficient that the measurements may be made without significant loss of accuracy, see IEC 60500, [1], [13].

NOTE 1 The level of electrical noise may degrade the accuracy when making electrical measurements.

NOTE 2 The signal amplitude should be at least 20 dB greater than the noise level.

NOTE 3 The level of broad-band interfering noise can be reduced by the use of a band-pass filter with a bandwidth sufficiently wide to allow the signal to pass through without distortion.

NOTE 4 In the presence of electrical noise, the signal to noise ratio may be improved by averaging of repeated signals. For random noise, averaging N signals will improve the signal to noise ratio by a factor of square root of N.

7.3.5 Cross-talk and acoustic interference

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

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

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

NOTE See 8.6.5.

7.3.6 Integral preamplifiers

Where a hydrophone has an integral preamplifier, the sensitivity shall be expressed as end-of-cable sensitivity (including the performance of the preamplifier).

NOTE Where a hydrophone has an integral preamplifier, corrections for electrical loading by extension cables or measuring instruments are unnecessary.

7.4 Measurement of projector current

The current through the projector shall be determined either by a calibrated current transformer (producing a voltage proportional to the drive current), or by measuring the voltage drop across a small, calibrated resistor (value of only a few ohms) in a series with the projector.

NOTE The first method is the preferred method.

7.5 Measurement of transfer impedance

The electrical transfer impedance between a projector and a hydrophone shall be calculated from the measured complex values of the projector current and hydrophone voltage.

For highest accuracy, the current shall be measured through the same measuring channel as the hydrophone voltage (the measuring channel may consist of an amplifier, filter, digitizer, etc.).

NOTE 1 In the latter case, the instruments used in the measuring channel will not require absolute calibration.

NOTE 2 If required, a calibrated attenuator may be used to equalize the voltage representing the projector current with the hydrophone voltage. This will minimize errors due to non-linearity in the measuring channel.

NOTE 3 Because this impedance depends on the field conditions and the electrical load conditions of the projector and the hydrophone, these conditions as well as the electrical terminals where the voltage and the current are measured, are specified. If the hydrophone is placed in the far field of the projector, the transfer impedance is inversely proportional to the distance d between the reference centres of the projector and the hydrophone:

$$Z_{\mathrm{PH}}\, d = \mathrm{constant} \tag{2}$$

8 Free-field reciprocity calibration

8.1 General principle

For calibrations with the smallest obtainable uncertainty, the primary calibration of hydrophones in free-field conditions (see 3.13) is undertaken using a method based on the principle of reciprocity. The frequency range of calibration is generally restricted to frequencies between 1 kHz and 1 MHz [1], [2], [12], [14] to [51], see IEC 60866, IEC 60500.

At least three transducers shall be used for the calibration technique, of which at least one shall be reciprocal.

Two of the transducers shall be placed under water in free-field conditions separated at a known distance d, far from the limits of the water volume with their axes directed towards each other.

Using one of them as a projector and the other as a hydrophone, the electrical transfer impedance shall be determined at a number of frequencies throughout the frequency range of interest (see 7.5).

With at least three pairs, formed with at least three transducers, at least three independent electrical transfer impedances shall be obtained. From these quantities, the free-field sensitivity of the hydrophone to be calibrated and all reciprocal transducers, as well as the transmitting response to current of each projector and all reciprocal transducers shall be calculated at each frequency, yielding the required frequency response curves of the transducers involved.

NOTE With a perfect sound reflector, such as the water surface, a reciprocity calibration is possible with only one reciprocal transducer.

8.2 Theory

8.2.1 Calibration without phase

NOTE The reciprocity principle states that, for any reciprocal transducer, the free-field sensitivity, divided by the transmitting response to current, is equal to a known value: the free-field reciprocity parameter. If the quotient of two quantities is known, as well as their product, the quantities can be calculated.

The product of the free-field sensitivity and the transmitting response to current shall be measured with the free-field reciprocity calibration technique, using one projector, one hydrophone and one reciprocal transducer.

Let a current I_P flow through a projector P with a transmitting response to current S_P. At a distance d from its reference centre and in the reference direction specified in the definition of S_P, the projector generates a sound pressure p which shall be calculated by:

$$p = \frac{S_\mathrm{P} I_\mathrm{P}}{d} \tag{3}$$

where spherical spreading of the sound energy from the projector is assumed.

Place a hydrophone H with free-field sensitivity M_H, in this sound field so that its reference centre is a distance d_1 from the reference centre of the projector P, producing an open circuit voltage U_PH given by:

$$U_\mathrm{PH} = M_\mathrm{H} p = \frac{M_\mathrm{H} S_\mathrm{P} I_\mathrm{P}}{d_1} \tag{4}$$

The electrical transfer impedance magnitude $\left|Z_\mathrm{PH}\right|$ of this transducer pair shall be calculated by:

$$\left|Z_\mathrm{PH}\right| = \frac{U_\mathrm{PH}}{I_\mathrm{P}} = \frac{M_\mathrm{H} S_\mathrm{P}}{d_1} \tag{5}$$

In a second step, determine the electrical transfer impedance magnitude $\left|Z_\mathrm{PT}\right|$, after replacement of the hydrophone H by a reciprocal transducer T, by:

$$\left|Z_\mathrm{PT}\right| = \frac{U_\mathrm{PT}}{I_\mathrm{P}} = \frac{M_\mathrm{T} S_\mathrm{P}}{d_2} \tag{6}$$

where d_2 is the distance between the reference centres of the reciprocal transducer T and the projector P.

In a third step, determine the electrical transfer impedance magnitude $\left|Z_{\mathrm{TH}}\right|$ as follows:

$$\left|Z_{\mathrm{TH}}\right| = \frac{U_{\mathrm{TH}}}{I_{\mathrm{T}}} = \frac{M_{\mathrm{H}} S_{\mathrm{T}}}{d_3} \tag{7}$$

where d_3 is the distance between the reference centre of the reciprocal transducer T and the hydrophone H.

NOTE In this case, the transducer T is used as a projector, and H again as a hydrophone.

Now it can easily be shown that:

$$\frac{\left|Z_{\mathrm{PT}}\right|\left|Z_{\mathrm{TH}}\right|}{\left|Z_{\mathrm{PH}}\right|} = \frac{M_{\mathrm{T}} S_{\mathrm{T}} d_1}{d_2 d_3} \tag{8}$$

The distance between the projector and the hydrophone shall be large enough so that the hydrophone is in the far field of the projector (see 3.12) and that the hydrophone receives a substantially plane wave (see also 8.3).

For a reciprocal transducer, the quotient of the free-field sensitivity and the transmitting response to current is equal to the spherical wave reciprocity parameter $2d_0/\rho f$ at the reference distance of $d_0 = 1\ \mathrm{m}$:

$$\frac{M_{\mathrm{T}}}{S_{\mathrm{T}}} = \frac{2}{\rho f} \tag{9}$$

where ρ is the density of the water and f is the frequency.

As the product and the quotient of the free-field sensitivity M and the transmitting response to current S of the transducer T are known, the values of M and S shall be calculated from equations (8) and (9) as follows:

$$M_{\mathrm{T}}^2 = \frac{2 d_2 d_3}{\rho f d_1} \frac{\left|Z_{\mathrm{PT}}\right|\left|Z_{\mathrm{TH}}\right|}{\left|Z_{\mathrm{PH}}\right|} \tag{10}$$

$$S_{\mathrm{T}}^2 = \frac{\rho f d_2 d_3}{2 d_1} \frac{\left|Z_{\mathrm{PT}}\right|\left|Z_{\mathrm{TH}}\right|}{\left|Z_{\mathrm{PH}}\right|} \tag{11}$$

Using equations (7) and (11) calculate for the sensitivity of the hydrophone M_{H}:

$$M_{\mathrm{H}}^2 = \frac{2 d_1 d_3}{\rho f d_2} \frac{\left|Z_{\mathrm{PH}}\right|\left|Z_{\mathrm{TH}}\right|}{\left|Z_{\mathrm{PT}}\right|} \tag{12}$$

Similarly, using equations (5) and (12), calculate the transmitting response to current S_{P} of the projector P:

$$S_{\mathrm{P}}^2 = \frac{\rho f d_1 d_2}{2d_3} \frac{|Z_{\mathrm{PH}}||Z_{\mathrm{PT}}|}{|Z_{\mathrm{TH}}|} \tag{13}$$

NOTE 1 A better statistical accuracy is obtained and the reciprocity can be verified if more than one transducer is reciprocal. If, for example, the projector P can also be used as a hydrophone, the electrical transfer impedance magnitude $|Z_{\mathrm{TP}}|$ can also be determined. Now it can be shown by the principle of reciprocity that $|Z_{\mathrm{TP}}|$ is equal to $|Z_{\mathrm{PT}}|$. Thus, $|Z_{\mathrm{PT}}|$ can also be obtained twice, once using P as a projector and T as a hydrophone and a second time using T as a projector and P as a hydrophone.

Any difference between these two values at the same frequency indicates lack of reciprocity or linearity, or may be due to a measuring error. The uncertainty of the mean value may be lower than that of either value alone.

NOTE 2 If the calibration is performed with more than three transducers and if two or more are reciprocal, the uncertainty may be reduced because the sensitivity can be calculated several times, using independent results from different combinations of transducers. The mean value of all results at the same frequency possesses a lower statistical uncertainty than each value alone.

8.2.2 Calibration with phase

The phase angle of the free-field sensitivity shall also be determined by extending the measurements to include phase.

NOTE 1 All of the pressures, input currents, output voltages, electrical transfer impedances, transmitting responses, and free-field sensitivities are now complex; they include both amplitude and phase. For example, equation (3) for the pressure produced by the projector P at the hydrophone H becomes:

$$p = \exp\left[jk\left(d_0 - d_1\right)\right] \frac{S_{\mathrm{P}} I_{\mathrm{P}}}{d_1} \tag{14}$$

where the distance d_1 is measured from the reference centre of the projector to the reference centre of the hydrophone. The wavenumber $k = 2\pi f / c$, where c is the speed of sound in the surrounding medium. The reference distance d_0 used in the definition of the transmitting response is equal to 1 m.

The complex electrical transfer impedance Z_{PH} shall be calculated by:

$$Z_{\mathrm{PH}} = \exp\left[jk\left(d_0 - d_1\right)\right] \frac{M_{\mathrm{H}} S_{\mathrm{P}}}{d_1} \tag{15}$$

Similarly calculate the electrical transfer impedances Z_{PT} and Z_{TH} as follows:

$$Z_{\mathrm{PT}} = \exp\left[jk\left(d_0 - d_2\right)\right] \frac{M_{\mathrm{T}} S_{\mathrm{P}}}{d_2} \tag{16}$$

$$Z_{\mathrm{TH}} = \exp\left[jk\left(d_0 - d_3\right)\right] \frac{M_{\mathrm{H}} S_{\mathrm{T}}}{d_3} \tag{17}$$

where d_2 is the distance between the reference centres of P and T and d_3 is the distance between the reference centres of T and H.

Equations (15) to (17) shall be combined to produce the complex equivalent of equation (8):

$$\frac{Z_{\mathrm{PT}}\,Z_{\mathrm{TH}}}{Z_{\mathrm{PH}}} = exp\left[\,jk\left(d_0 + d_1 - d_2 - d_3\right)\right]\frac{M_{\mathrm{T}}S_{\mathrm{T}}d_1}{d_2d_3} \tag{18}$$

Using the complex spherical wave reciprocity parameter calculate, instead of equation (9):

$$\frac{M_{\mathrm{T}}}{S_{\mathrm{T}}} = \frac{2}{j\,\rho\,f}\exp\left(j\,k\,d_0\right) \tag{19}$$

Expressions corresponding to (10) and (11) shall be obtained by combining equations (18) and (19):

$$M_{\mathrm{T}}^2 = \frac{2d_2d_3}{j\,\rho\,fd_1}\exp\left[\,jk\left(d_2 + d_3 - d_1\right)\right]\frac{Z_{\mathrm{PT}}\,Z_{\mathrm{TH}}}{Z_{\mathrm{PH}}} \tag{20}$$

$$S_{\mathrm{T}}^2 = \frac{j\,\rho\,fd_2d_3}{2d_1}\exp\left[\,jk\left(d_2 + d_3 - d_1 - 2d_0\right)\right]\frac{Z_{\mathrm{PT}}\,Z_{\mathrm{TH}}}{Z_{\mathrm{PH}}} \tag{21}$$

Equations (17) and 21) shall be used to derive the following expression for the complex free-field sensitivity of the hydrophone H.

$$M_{\mathrm{H}}^2 = \frac{2d_1d_3}{j\,\rho\,fd_2}\exp\left[\,jk\left(d_1 + d_3 - d_2\right)\right]\frac{Z_{\mathrm{PH}}\,Z_{\mathrm{TH}}}{Z_{\mathrm{PT}}} \tag{22}$$

Similarly, the expression for the transmitting response S_{P} corresponding to (13) shall be calculated by:

$$S_{\mathrm{P}}^2 = \frac{j\,\rho\,f\,d_1\,d_2}{2d_3}\exp\left[\,jk\left(d_1 + d_2 - d_3 - 2\,d_0\right)\right]\frac{Z_{\mathrm{PH}}\,Z_{\mathrm{PT}}}{Z_{\mathrm{TH}}} \tag{23}$$

NOTE 2 The difficulty of determining the phase of M_{H} by this method lies in accurately determining both the sound speed and the measurement distances d_1, d_2 and d_3. For example, at 100 kHz in water, an error of only 1,0 mm in any one of the distances gives a phase error of about 12°.

To avoid this, position the three transducers $\mathrm{P, H,}$ and T in a straight line with H located between P and T, then $d_2 = d_1 + d_3$. Then simplify equation (22) to:

$$M_{\mathrm{H}}^2 = \frac{2d_1d_3}{j\,\rho\,fd_2}\frac{Z_{\mathrm{PH}}\,Z_{\mathrm{TH}}}{Z_{\mathrm{PT}}} \tag{24}$$

NOTE 3 Since the distances and sound speed do not appear explicitly in a phase term in equation (24), the accuracy of the calculated phase of M_{H} is only limited by accuracy of the phase measurements of the voltages and currents and by positioning. A special measurement framework that can minimize positioning errors is illustrated by Figure 2.

Measurements shall be made as follows:

a) Mount the transducers as shown in Figure 2 with their reference centres separated by the distances d_1, d_2 and d_3, where $d_3 = d_2 - d_1$. Align their reference directions with P pointing toward H and T. Determine the complex electrical transfer impedance Z_{PH} from the input current to P and the output voltage from H.

b) Remove the hydrophone with its hanger from the framework. Determine the complex electrical transfer impedance Z_{PT} from the input current to P and the output voltage from T.

c) Replace the hydrophone with its hanger in the framework and rotate about its reference centre so that T now points toward H and the distance d_3 is maintained between the reference centres of H and T. Determine the complex electrical transfer impedance Z_{TH} from the input current to T and the output voltage from H.

Calculate the magnitude and phase angle of the free field sensitivity of the hydrophone from equation (24) using the measured electrical transfer impedances [23].

NOTE 3 The resulting sensitivity is representative of both the hydrophone and its hanger.

NOTE 4 The calibration should be performed using the same hanger that will support the hydrophone when it is used for field measurements. (See 6.2)

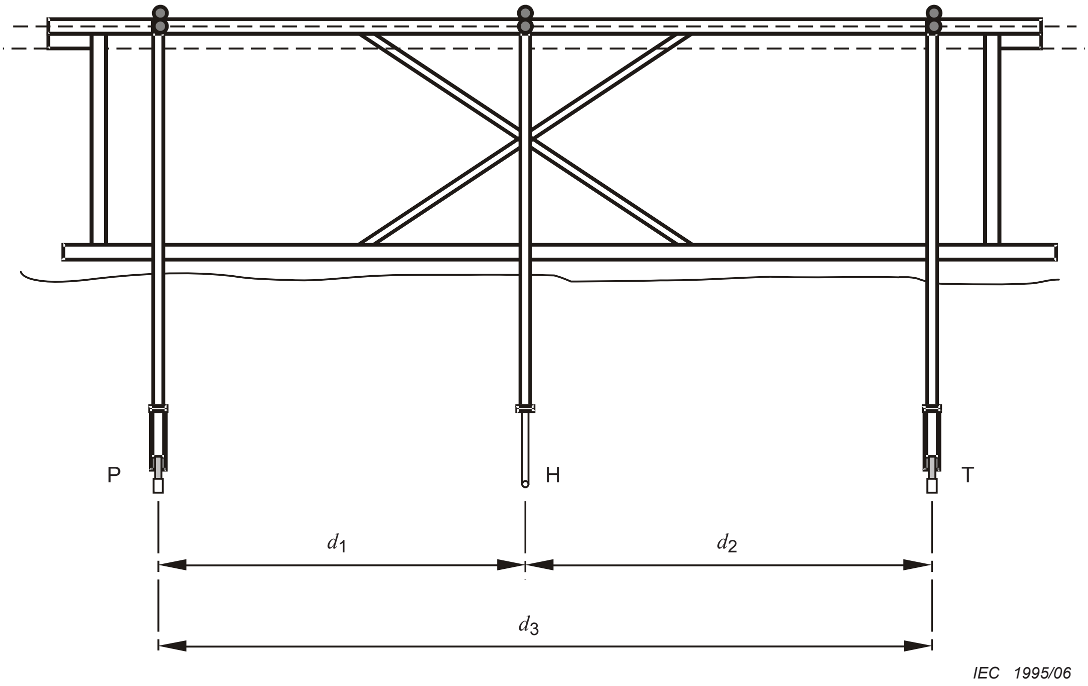


Figure 2 – Measurement framework for supporting in-line the three transducers: a projector P, a reciprocal transducer T, and a hydrophone H to be calibrated

8.3 Separation distance

The distance d between the projector and the hydrophone shall be large enough to minimize errors due to the finite size of the transducers.

For this purpose, the separation shall be larger than the size of the largest transducer, and the hydrophone shall be in the far field of the source (see 3.12).

For the two transducers with maximum dimensions of the sensitive areas of a_1 and a_2 respectively, the distance shall be chosen according to the relation:

$$d > \frac{a_1^{\ 2} + a_2^{\ 2} + a_1 a_2}{\lambda} \qquad (25)$$

and simultaneously:

$$d > 5a_1 \text{ and } d > 5a_2 \qquad (26)$$

in order to reduce the error due to lack of spherical divergence to below 0,3 dB. To obtain a separation that reduces the uncertainty to less than 0,2 dB, the right hand side of equation (25) shall be multiplied by a factor of 1,2.

When measuring the directional response of a transducer, the distance between the projector and the hydrophone shall be somewhat larger than that given by (25) and (26). The distance shall be no less than twice that given by equation (25) or equation (26), whichever is larger, see Annex C and [1], [41] and [42].

8.4 Minimum distance from transducers to boundary surface

With tone-burst signals, interference with the reflections shall be eliminated by choosing the minimum distance from the transducers to each boundary surface (water surface, bottom and side walls) such that the delay of the reflected signals with respect to the direct signal is greater than the burst length (see Annex C).

With continuous signals, the distance from the transducers to each boundary shall be such that the variation in the direct sound pressure, due to the interference with the reflections from those boundaries is less than 0,3 dB

NOTE The minimum distance to the boundaries, satisfying this requirement, depends also on the directivity of the transducers, the reflection coefficient of the boundary surfaces and on the signal type: sinusoidal or gated tone burst signals.

8.5 Frequency limitation

8.5.1 High-frequency limit

Due consideration shall be given to the limitations of the method at high frequencies, and the influence of any limitations shall be reflected in the evaluation of overall uncertainty.

NOTE 1 The high frequency limit is governed by a number of factors. These are described in detail in Annex C (see C.2.9).

NOTE 2 At frequencies greater than 0,5 MHz, consideration should be given to the use of the alternative method described in IEC 60866.

8.5.2 Low frequency limit

Due consideration shall be given to the limitations of the method at low frequencies, and the influence of any limitations shall be reflected in the evaluation of overall uncertainty.

NOTE 1 The lowest frequency for calibrations is limited by several factors. These are described in detail in Annex C (see C.2.10).

NOTE 2 For most large test tank facilities of minimum dimension 5 metres or greater, the practical low frequency limit for calibration of hydrophones will be of the order of 1 kHz or 2 kHz depending on the Q-factor of the transducer.

8.6 Measurements and checks

8.6.1 General

The calibration shall be performed in accordance with Clauses 6 and 7. See IEC 60866, IEC 60500, [1], [2], [8], [12], and [24] to [51].

8.6.2 Alignment

Before calibration, a reference direction shall be defined for each transducer.

NOTE 1 This reference direction is the direction for which the free-field calibration will be valid. Often, the reference direction will coincide with the principal axis of the transducer (see 3.1, 3.5, 3.18 and 3.23).

For omnidirectional hydrophones with a symmetric construction, the reference direction shall be indicated by a mark on the body of the hydrophone.

NOTE 2 The direction may be chosen by determining the maximum response angle of the hydrophone at a stated frequency by undertaking a directional response measurement (see Annex A).

Before the measurement of each electrical transfer impedance, the relevant transducer pair shall be oriented such that the reference directions of the transducers are aligned.

NOTE 3 This alignment may be performed either manually, or mechanically using special rigging or positioning system.

NOTE 4 For transducers that show appreciable directivity about their principal axis (for example, piston transducers), the transducers may be aligned acoustically by looking for the maximum received signal at a specific frequency. Sometimes the reference direction may be chosen in the portion of the directional response pattern where the response does not change significantly with the directional angle.

8.6.3 Electrical measurements

The electrical measurement of open circuit voltage and projector current shall be made in accordance with 7.3 and 7.4.

8.6.4 Spherical-wave verification

Due consideration shall be given to the deviation from the assumed spherical-wave field, and the influence of any deviation shall be reflected in the evaluation of overall uncertainty.

NOTE The existence of a spherically-spreading acoustic field may be verified by comparison of the electrical transfer impedance magnitudes when the distance between projector and hydrophone is varied. See 7.5, NOTE 3 and Annex C (C.2.11). In ideal conditions, it should be possible to obtain deviation of less than ±2 %. Variation of greater than ±5 % may indicate additional problems (e.g. from boundary reflections) and should be investigated further.

8.6.5 Evidence of interference effects

Care shall be taken to ensure that interference from electrical cross-talk is not present during measurements. When tone-burst signals are used, the cross-talk shall be eliminated by time-windowing. In order to avoid interference when electrical cross-talk is present, the tone-burst duration shall not be greater than the acoustic propagation delay, so that the two signals cannot overlap in time.

With tone-burst signals, a tone-burst repetition rate shall be chosen that is low enough for all reverberation in the tank to die away before transmission of the next pulse.

NOTE 1 Further details on the influence of reflections are given in Annex C (see C.2.12).

NOTE 2 Where smooth periodic ripples can be observed in a plot of electrical transfer impedance (or sensitivity) against frequency, this is an indication that there is likely to be acoustic reflections present leading to constructive and destructive interference effects. If the frequency interval between successive peaks in the plot is Δf, and c is the speed of sound in the medium, the path difference, Δd, between the direct and reflected signals arriving at the hydrophone shall be calculated by [1]:

$$\Delta d = \frac{c}{\Delta f} \tag{27}$$

8.6.6 Reciprocity verification

Since the method depends upon the assumption that at least one transducer is reciprocal, this assumption shall be verified. The reciprocity of a pair of reciprocal transducers shall be verified by comparison of the electrical transfer impedance magnitudes when the functions of the transmitter and receiver are interchanged without altering the transducer positions (i.e., by comparing Z_{PT} and Z_{TP} where both P and T are reciprocal) [12].

Note 1 For well-behaved transducers used within their main operating range, it is possible to obtain agreement between the electrical transfer impedances of a few percent.

NOTE 2 Disagreement of greater than ±5 % indicates that at least one of the transducers might not be behaving in a reciprocal manner. The use of a third reversible transducer in the reciprocity verification may reveal which of the transducers is non-reciprocal. In a reciprocity calibration, non-reciprocal transducers may only be used as a projector or hydrophone (as appropriate).

If large discrepancies between Z_{PT} and Z_{TP} occur because one (or both) transducers is driven too hard, resulting in non-linear behaviour, then the amplitude of the drive signal to the transducers shall be reduced. However, if such a reduction results in unacceptably low signal-to-noise ratio, consideration shall be given to the use of alternative transducers.

For the lowest uncertainty in reciprocity calibrations, the reciprocal transducers shall be used within their normal operating band (typically up to the frequency of the first resonance for a piezoelectric transducer).

NOTE 3 Use of a transducer at frequencies outside this band (for example, at frequencies much greater than the resonance frequency) may result in non-reciprocal behaviour and degradation in the accuracy of the calibration.

NOTE 4 Calibration of a hydrophone over a broad frequency range may require the use of several different reciprocal transducers to cover the complete range with sufficiently small uncertainty.

NOTE 5 If the transducers in the reciprocity verification are identical in construction, they may be nonlinear to the same extent and still appear reciprocal. Therefore, the reciprocity verification should be performed using transducers of different construction before either may be assumed to be reciprocal.

8.6.7 Linearity verification

If there is any doubt regarding the linearity of the transducers, the linearity of each pair of transducers shall be verified by comparison with the magnitudes of the electrical transfer impedance at different levels of the projector current, within the dynamic range of the system, at the same frequency. Starting at a level of 20 dB higher than the background noise level up to the highest level that will be used, the magnitude of the transfer impedance shall remain constant within ±5 %.

NOTE Care should be taken that during the actual calibration, the signal levels are kept within the range of linearity. As this range may be different for each pair of transducers, careful observation of the signal levels is necessary.

8.6.8 Free-field sensitivity

By means of equations (10) and (12) of 8.2, the free-field sensitivities M_{H} of the hydrophone H to be calibrated and M_{T} of the reciprocal transducer T shall be calculated from the electrical transfer impedance magnitudes measured at each frequency. If the projector P is reciprocal, its free-field sensitivity shall be calculated from its transmitting response to current S_{P} using the reciprocity relationship given by equation (9) with T replaced by P.

NOTE 1 If the projector is not reciprocal, then its calculated receive sensitivity has no physical meaning.

For the lowest uncertainty, the calibration shall be repeated a number of times and the mean of the results at each frequency shall be used as the final value of sensitivity. The repeated calibrations shall be truly independent, with the transducers removed from the water and remounted between each calibration.

NOTE 2 If a different separation distance is used for some of the repeated calibrations, this will be of assistance in assessing some of the assumptions in the method (free-field conditions, spherical-wave field, etc.) since the sensitivity should be invariant with separation distance.

The standard deviation shall be determined and used in the calculation of uncertainties, see Annex D.

NOTE 3 Lack of good repeatability indicates a problem with the calibration and the cause should be investigated. With care, it is possible to achieve standard deviations as low as 1 % for hydrophones over their operating range.

8.6.9 Transmitting response to current

By means of equations (11) and (12) of 8.2, the transmitting response to current S_{T} of the reciprocal transducer T and S_{P} of the projector P shall be calculated from the electrical transfer impedance magnitudes measured at each frequency. If the hydrophone H is reciprocal, its transmitting response to current S_{H} shall be calculated from its free-field sensitivity by use of equation (9) with T replaced by H.

NOTE The transmitting response has no physical meaning where the transducer cannot be used as a sound source (for example, for a hydrophone with an integral preamplifier, which precludes its use as a projector).

8.7 Uncertainty

NOTE 1 The evaluation of uncertainty for the free-field reciprocity calibration method involves many components (see Annex D).

In accordance with the linearity, reciprocity and free-field conditions specified in 8.6.4 to 8.6.7, the overall expanded uncertainty (95 % confidence levels) shall be less than 1 dB in magnitude. Under the same conditions, the overall expanded uncertainty shall be less than 6° in phase for frequencies up to 100 kHz.

NOTE 2 As the frequency increases above 100 kHz, the achievable uncertainty for phase increases to greater than 6°.

9 Free-field calibration by comparison

9.1 Principle

9.1.1 General

The calibration of hydrophones in free field conditions (see 3.13) by comparison with a standard hydrophone or by using a calibrated projector is described. Calibration of a hydrophone by comparison requires either a calibrated hydrophone and an auxiliary projector, or a calibrated projector [24].

9.1.2 With a standard hydrophone

The sound pressure at a point in the sound field, generated by the auxiliary projector, is measured with a calibrated standard hydrophone. Then the calibrated hydrophone is replaced by the unknown hydrophone. The ratio of the open circuit voltages of the two hydrophones is equal to the ratio of their free field sensitivities.

9.1.3 With a calibrated projector

The sound pressure at a point in the sound field, generated by a calibrated projector, is determined by measuring either the current through the projector or the voltage across the projector and using the transmitting current or voltage response, respectively, and the test distance. Measurement of the open circuit voltage of a hydrophone placed in the known sound field determines the free field sensitivity of that hydrophone.

9.2 Comparison with a standard hydrophone

9.2.1 Separation distance

The distance d between the projector and the hydrophone shall be chosen according to the instructions given in 8.3.

NOTE A distance smaller than that required for free-field conditions may be acceptable when the unknown hydrophone is compared with a calibrated hydrophone at the same place in the sound field. This is possible when the two hydrophones are exposed to the same acoustic pressure and neither hydrophone responds to acoustic pressure gradients. To achieve this, the two hydrophones should essentially be identical in structure, or both should have dimensions much less than an acoustic wavelength [41].

9.2.2 Transducer depth

To avoid strong fluctuations introduced in the sound field by reflections from the water surface, the depth of the transducers shall be chosen according to the requirements specified for reciprocity calibrations (see 8.4).

9.2.3 Signal type

The signal type shall be the same as specified for the reciprocity calibration (see 8.5).

9.2.4 Measurements

The calibration shall be performed under the conditions specified in Clause 6.

The open-circuit voltage of the unknown hydrophone in the sound field shall be measured at the end of the cable (see 7.3).

The open-circuit voltage at the calibrated standard hydrophone electrical terminals shall be measured as specified with the calibration curve of that hydrophone.

When this measurement is performed in air, the measurement shall be carried out in an anechoic room as is generally used for the calibration of microphones.

NOTE This measurement can be performed in water or in air. In the latter case, a calibrated microphone may replace the standard hydrophone.

9.2.5 Free-field sensitivity

The sensitivity of the hydrophone under test shall be calculated from the ratio of the open-circuit voltages of both hydrophones and the sensitivity of the standard hydrophone.

NOTE Because the sensitivity of the standard hydrophone is known, the sensitivity of the hydrophone under test can be calculated.

9.2.6 Uncertainty

The overall uncertainty for the calibration shall be determined and expressed with the value for the sensitivity. With care and when using hydrophones within their main operating range, an overall uncertainty (95 % confidence levels) shall be achieved which is 1,5 dB or better.

NOTE Hydrophone calibration by a comparison method will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference hydrophone will inevitably introduce a large Type B component of uncertainty. More guidance on assessment of uncertainties is given in Annex D.

9.3 Calibration with a calibrated projector

9.3.1 Separation distance

The distance between the projector and the hydrophone shall be chosen in accordance with 9.2.1. In order to reduce errors due to non-spherical spreading and diffraction, the separation distance shall be close to the specified calibration distance of the projector, provided that the size of the hydrophone is small enough for the relations (25) and (26) to be fulfilled.

NOTE The projector has been calibrated at a certain distance or within a given range of distances.

9.3.2 Transducer depth

The depth of the transducers is chosen in accordance with the specifications for reciprocity calibration (see Clause 8).

9.3.3 Signal type

The signal type shall be in accordance with 8.5.

NOTE If the projector has been calibrated with a specific type of signal, it is advisable to use the same type when that projector acts as a calibrated sound source.

9.3.4 Measurements

The calibration shall be performed under the conditions specified in Clause 6. Measurement of the open-circuit voltage U_{PH} shall be in accordance with 7.3. Measurement of the projector current I_{P} shall be in accordance with 7.4. The electrical transfer impedance magnitude $\left|Z_{\mathrm{PH}}\right|$ shall be obtained in accordance with 7.5.

The free-field verification shall be performed in accordance with 8.6.4 and 8.6.5, and the linearity verification according to 8.6.7.

With the measured values of U_{PH}, I_{P} and $\left|Z_{\mathrm{PH}}\right|$ and with the known transmitting response to current S_{P} of the projector, the free field sensitivity M_{H} of the hydrophone shall be calculated with the following equation, derived from the equations (4) and (5).

$$M_{\mathrm{H}} = \frac{d\,U_{\mathrm{PH}}}{S_{\mathrm{P}} I_{\mathrm{P}}} = \frac{d\left|Z_{\mathrm{PH}}\right|}{S_{\mathrm{P}}} \tag{28}$$

NOTE The electrical terminals of the hydrophone to which the calibration refers should be specified with the result.

9.3.5 Uncertainty

The overall uncertainty for the calibration shall be determined and expressed with the value for the sensitivity. With care and when both the hydrophone and the projector are used within their main operating range, an overall expanded uncertainty (95 % confidence levels) of 2 dB or better shall be achieved.

NOTE Hydrophone calibration by use of a standard projector will in general have higher uncertainty than a primary method (such as a method based on free-field reciprocity) since the uncertainty in the calibration of the reference projector will inevitably introduce a large component of uncertainty. The stability of the projector and the potential lack of free-field conditions may also contribute to overall uncertainty. More guidance on assessment of uncertainties is given in Annex D.

10 Calibration by hydrostatic excitation

10.1 Principle

The calibration of hydrophones without a standard transducer in the frequency range from 0,01 Hz to 2 Hz by harmonically changing hydrostatic pressure is described. A method of absolute calibration of hydrophones in a small chamber is used [1], [52].

10.2 Determination of equivalent pressure

10.2.1 General

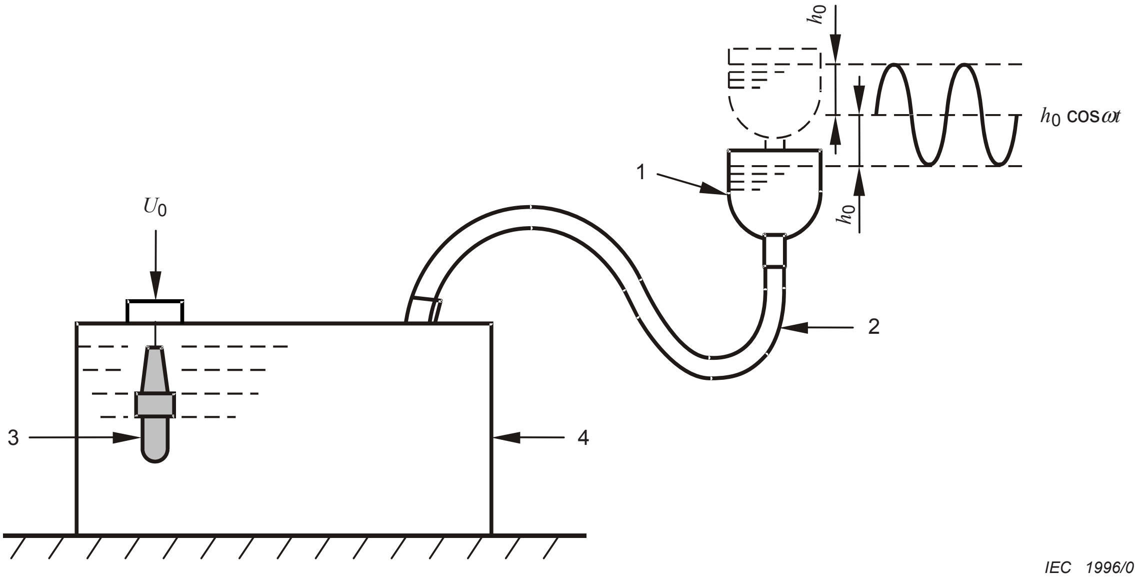
Connect a closed measuring chamber by means of a flexible tube with an open small vessel with the water level in the vessel always higher than the measuring chamber (see Figure 3).

NOTE The open vessel moves vertically at a harmonic frequency.

The displacement of the water level in the open vessel shall be expressed as:

$$h = h_0 \cos \omega t \tag{29}$$

where h_0 is the amplitude of the displacement of the open vessel and ω is the angular frequency of vibration.



IEC 1996/06

Key

1 Open vessel
2 Flexible tube
3 Hydrophone
4 Measuring chamber

Figure 3 – Diagram of the method of hydrostatic excitation

Variation of the water level in the vessel produces an alternating hydrostatic pressure in the closed chamber:

$$p = p_0 \cos \omega t \tag{30}$$

where p_0 is the amplitude of the alternating hydrostatic pressure. The alternating hydrostatic pressure p is used as an equivalent pressure to calibrate hydrophones. At low frequencies (less than 0,5 Hz) its amplitude is calculated according to the following equation:

$$p_0 = \rho \, \mathrm{g} \, h_0 \tag{31}$$

where ρ is the density of water and g is the gravitational constant.

At high frequencies, the alternating hydrostatic pressure p is influenced by both the Helmholtz resonance of the system and the inertia of the water in the open vessel and the flexible tube. The resonance of the system will increase the alternating hydrostatic pressure, and the inertia of the water will reduce the alternating hydrostatic pressure. As a result, the amplitude of the alternating hydrostatic pressure in the measuring chamber shall be determined using the following equation:

$$p_0 = \rho\, \mathrm{g}\, h_0 \left|K_0\right| \left(1 - \frac{\omega^2}{\mathrm{g}} H_\mathrm{e} \right) \tag{32}$$

where $\left|K_0\right|$ is the factor by which the alternating hydrostatic pressure increases. H_e, called the equivalent height (having the dimension of the length), is influenced by the inertia of the water in the vessel and the tube.

10.2.2 Determination of the increasing factor

At very low frequencies, the Helmholtz resonance of the system is described using one-dimensional lumped parameters. The magnitude of the increasing factor $\left|K_0\right|$ shall be calculated by the expression:

$$\left|K_0\right| = \frac{1}{\left(1 - \frac{\omega^2}{\omega_\mathrm{r}^2}\right)\sqrt{1 + \left(\frac{\omega}{Q\omega_\mathrm{r}}\right)^2 \Big/ \left(1 - \frac{\omega^2}{\omega_\mathrm{r}^2}\right)^2}} \tag{33}$$

where ω_r is the resonance angular frequency of the system and Q is the mechanical quality factor.

Under conditions of $\omega_\mathrm{r} >> \omega$ and $Q > 2$, equation (33) shall be expressed with sufficient accuracy as:

$$\left|K_0\right| \approx 1 + \left(\frac{\omega}{\omega_\mathrm{r}}\right)^2 \tag{34}$$

10.2.3 Measurement of the resonance frequency of the calibration system

The resonance frequency ω_r shall be measured and verified after the calibration system has been completed. For this purpose, mount a piezoelectric projector into the measuring chamber and drive with a sweep generator in the frequency range containing ω_r. Install a hydrophone with constant sensitivity over this frequency range in the chamber and measure its open-circuit output voltage. The lowest resonance frequency of both the projector and the hydrophone shall be much greater than ω_r. The resonance frequency of the system shall be determined according to the frequency response of the output voltage of the hydrophone.

10.2.4 Determination of the equivalent height

10.2.4.1 General

The equivalent height H_e shall be determined in accordance with 10.2.4.2,. 10.2.4.3 or 10.2.4.4.

10.2.4.2 Alternating hydrostatic pressure null method

The alternating hydrostatic pressure in the measuring chamber shall be adjusted to zero by one of two different ways [53]:

a) By adding or removing water in the open vessel to change the water level, the alternating hydrostatic pressure p in the measuring chamber shall be adjusted to zero at a specified frequency ω_0. From equation (32), the equivalent height shall be calculated by:

$$H_e + \Delta H = g/\omega_0^2 \tag{35}$$

where ΔH is the change in water level and H_e is the initial equivalent height.

Change the water level again by an amount $-\Delta H$ to restore the equivalent height to its original value. The equivalent height shall then be calculated by:

$$H_e = g/\omega_0^2 - \Delta H \tag{36}$$

b) While keeping the water level in the open vessel at a suitable height, adjust the alternating hydrostatic pressure in the measuring chamber to zero by varying the frequency. The equivalent height is now equal to g/ω_0^2, where ω_0 is the frequency at which the alternating hydrostatic pressure null occurs. In this method, the water level of the open vessel shall be sufficient to ensure that ω_0 is higher than the upper frequency limit of the calibration range. If the water level is changed by an amount $-\Delta H$ to restore the alternating hydrostatic pressure to a suitable value, the equivalent height at this point shall be obtained using the expression (36).

10.2.4.3 Water level change method

With the water level in the open vessel at an instantaneous height, H_e, and the open vessel vibrating vertically at a frequency ω, measure the open-circuit voltage U_1 of a hydrophone in the measuring chamber. Change the water level of the open vessel by an amount ΔH, then measure the open-circuit voltage of the hydrophone, U_2. With these two measurements, the equivalent height shall then be determined according to the equation:

$$H_e = \frac{g}{\omega^2} + \frac{U_1 \Delta H}{\left(U_2 - U_1\right)} \tag{37}$$

NOTE ΔH is positive when the water level rises and is negative when the water level falls [53].

10.2.4.4 Two frequencies method

With the open vessel vibrating first at the frequency ω_1 and then at the frequency ω_2 (ω_1 and ω_2 shall be close to each other, differing by less than 0,6 rad/s), measure the corresponding open-circuit voltages U_1 and U_2 of the hydrophone in the closed chamber. The assumption shall be made that.

a) The sensitivity of the hydrophone is almost the same at two close frequencies, which are much lower than the resonance frequency of the hydrophone.

b) The hydrophone will suffer nearly the same influence of the Helmholtz resonance of the system at two closely spaced frequencies. In this case, the equivalent height shall be calculated by the expression:

$$H_\mathrm{e} = \mathrm{g}\frac{(U_2 - U_1)}{U_2\,\omega_1^2 - U_1\,\omega_2^2} \qquad (38)$$

NOTE The alternating hydrostatic pressure null method is the most accurate of the three methods. However, as this method requires that the frequency for the pressure null be beyond the calibration frequency range, the vibration device operates over a wider frequency range. The two-frequency method is the most convenient one. If the related assumption is satisfied, this method is also very accurate [53].

10.2.5 Calculation of the pressure sensitivity of hydrophones

The pressure sensitivity M_p of a hydrophone placed into the measuring chamber (see Figure 3) shall be calculated by:

$$M_\mathrm{p} = \frac{U_0}{p_0} \qquad (39)$$

where U_0 is the open-circuit voltage of the hydrophone and p_0 is the pressure in the chamber. The following conditions shall be met, when the pressure sensitivity M_p is equal to the free-field sensitivity M_H:

a) the diffraction factor of the hydrophone is unity,

b) the hydrophone has negligible response to particle velocity and pressure gradient,

c) either the frequency of calibration is sufficiently below the lowest resonance frequency of the hydrophone so that the sensitivity of the hydrophone is independent of acoustic impedance, or the apparent acoustic impedance of the hydrophone in the chamber is equal to the acoustic impedance in a free field.

NOTE This is assumed to be the case and M_H will be used in place of M_p for calibration using hydrostatic excitation.

10.3 Measurement of the sensitivity of hydrophones

By means of equation (39), the sensitivity M_H of each hydrophone shall be calculated from the ratio of the open-circuit voltage and the pressure existing on the hydrophone at each frequency.

The pressure p_0 shall be derived from the equation (32). If the calibration system and the water level of the open vessel are kept unchanged, the magnitudes of h_0, ω_r and H_e in the equations remain constant and shall be determined in advance. The magnitude of the pressure p_0 is also known in advance at each frequency so that only the open-circuit voltage U_0 of the hydrophone shall be measured for each calibration.

NOTE The instrument used to measure the output voltage of the hydrophone should have an input electrical impedance much higher than that of the hydrophone. (See 7.3.2). Instruments used for measuring voltage include digital voltmeter, digital oscilloscope and signal analyser.

Since the equivalent height H_e depends on the water level in the open vessel and the location of the flexible tube, the value of the equivalent height H_e shall be determined at each calibration session using the two frequencies method.

10.4 Design of vibration system

The design of the vibration system shall take into account the following.

a) As the displacement of the water level h is related to the equivalent pressure p, its amplitude h_0 shall be large enough to produce a sufficiently high equivalent pressure to ensure adequate excess of the measured signal over the noise. However, to keep the moving devices oscillating smoothly at the upper frequency limit of the system, the amplitude h_0 shall not be too large.

NOTE 1 In practice, when the calibration frequency is lower than 1 Hz or 2 Hz, a suitable amplitude for vibration displacement may be up to 20 mm or 5 mm, respectively.

b) For converting rotary motion to vertical linear simple harmonic motion, a special mechanism shall be designed.

NOTE 2 One type of such a mechanism involves fixing a pin eccentrically on a motor-drive disk. The pin slides in a groove of a yoke; the yoke and supporting rod are constrained to move in a vertical direction. As the disk rotates, the yoke and rod move up and down sinusoidally. The radius of the pin position is equal to the amplitude of displacement h_0. The frequency of linear motion can be expressed as:

$$f = \nu / 360 \qquad (40)$$

where ν is the rotational velocity of the motor drive in degrees per second.

c) In the design of the parts of the system consisting of the measuring chamber, the soft pipe and the open vessel, the Helmholtz resonance frequency ω_r shall be as far away from the calibration frequency ω as possible. The following condition shall be satisfied:

$$\omega_r \geq 20\omega \qquad (41)$$

so that, then:

$$|K_0| \approx 1 \qquad (42)$$

d) The calibration system shall be designed and installed in such a way that the influence of any stray vibration of the moving device on the open vessel is minimized. All necessary precautions shall be taken to avoid the direct coupling of any vibration.

e) To ensure uniform motion of the water, the acceleration of the open vessel shall be less than the acceleration due to gravity. This condition shall be expressed as:

$$\omega_0^2 h_0 << \mathrm{g} \tag{43}$$

NOTE 3 The drive disk can be driven in various ways. In order to control the rotational velocity v accurately with a computer, stepper motors are usually used. Moreover, to avoid the resonance point of the moving device at low frequency and to keep the open vessel moving smoothly in the vertical direction, it is recommended that dual stepper motors be used driven in a differential mode.

10.5 Uncertainty

The uncertainty in the calibration method shall be determined and stated with the value for the hydrophone sensitivity.

NOTE 1 The main sources of uncertainty for this method come from the amplitude of the displacement of the open vessel h_0, the vibration frequency ω, the increasing factor $|K_0|$, the open circuit voltage of the hydrophone U_0 and the equivalent height H_e.

NOTE 2 It is expected that the overall expanded uncertainty of the calibration can be less than 0,3 dB (95 % confidence levels) with careful practice.

10.6 Alternative method for hydrostatic excitation

As an alternative approach, the hydrostatic pressure may be varied by changing the depth of the hydrophone with simple harmonic motion. In this case the alternating pressure amplitude p_0 shall be given by equation (31) and the pressure sensitivity M_p shall be calculated from equation (39). When the conditions of 10.2.5 are met, the pressure sensitivity is equal to the free-field sensitivity M_H.

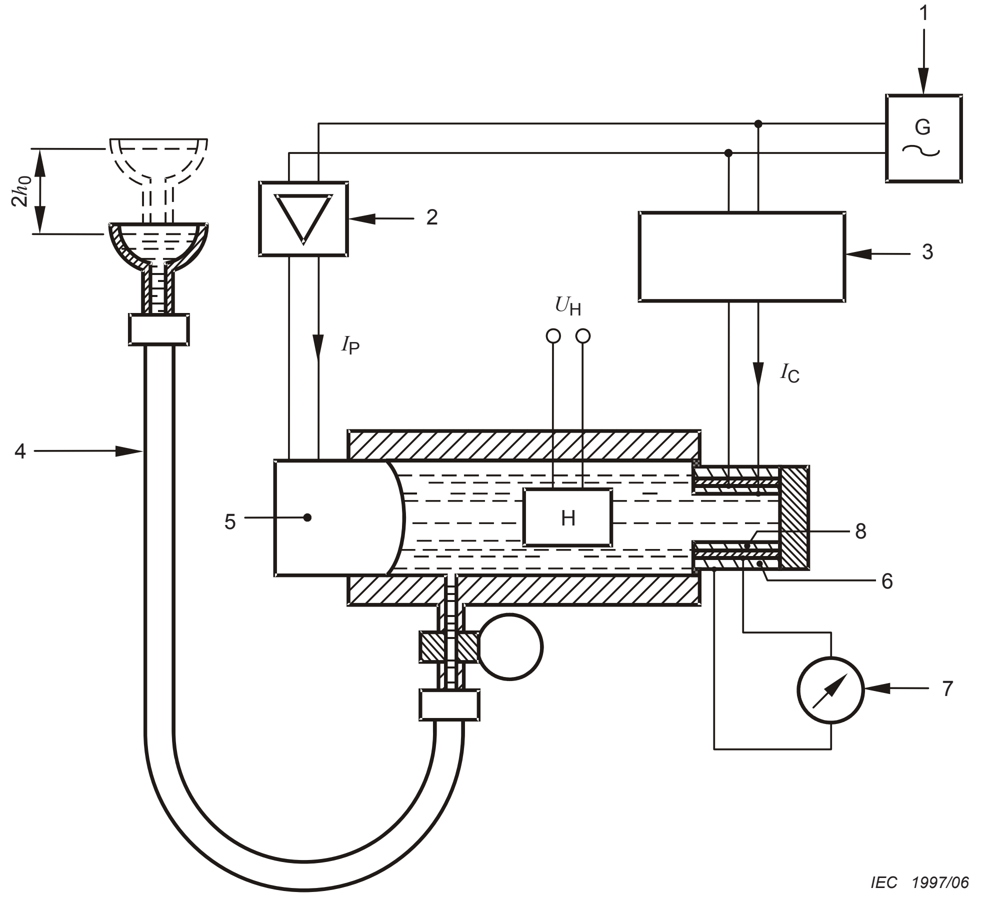
NOTE This method of hydrostatic excitation introduces sources of dynamic pressure that contribute to measurement uncertainty. The first source is the hydrodynamic flow around the hydrophone. This is a function of the hydrophone shape. The second source arises from inertial effects of the medium. It can be minimized by proper orientation of the hydrophone to reduce the displacement of water near the active face. For example, hydrophones with planar active faces can be oriented with the hydrophone face in a vertical plane. The third source arises from inertial effects within the hydrophone. This can often be minimized by orientation, although the optimum orientation might not be the same one that minimizes the inertial effects of the medium. The fourth source of unwanted dynamic pressure is turbulence. This can be minimized by making all fixtures as streamlined as possible. There is also the possibility that the harmonic motion of the hydrophone may excite a slosh resonance in the calibration chamber. These additional sources of uncertainty tend to increase with frequency and limit the upper frequency range for this technique. For frequencies up to 2 Hz, it is expected that the overall expanded uncertainty of the calibration can be less than 0,5 dB (95 % confidence levels) with careful practice [1], [54].

11 Calibration by piezoelectric compensation

11.1 Principle

A hydrophone is calibrated without a standard transducer, in a closed water-filled chamber, at frequencies at which the wavelength is sufficiently larger than the largest dimension of the chamber. A method of calibration of a hydrophone in a small closed chamber, without a standard transducer is used, in the frequency range from 1,0 Hz to 5 kHz [55] to [58].

NOTE The method of piezoelectric compensation is used when hydrophones have to be calibrated without the availability of a large water volume.



Key

1 Signal generator

2 Power amplifier

3 Phase and amplitude controls

4 Water column

5 Source projector

6 Displacement sensor of the null transducer

7 Null indicator

8 Driving shell of the null transducer

Figure 4 – Schematic drawing of the measuring system

11.2 Procedure

While being calibrated, place the hydrophone inside a closed, water-filled tank, equipped with a source projector and a piezoelectric null transducer (see Figure 4). Measure the magnitude of the alternating pressure produced by the source projector in the tank using the null transducer.

Fill the small annular gap between the shells with an elastic coupling substance.

NOTE 1 The null transducer consists of two coaxially mounted piezoelectric ceramic cylindrical shells. The inner shell acts as driving transducer, while the outer shell serves as displacement sensor.

Adjust the phase and amplitude of the voltage U_c at the electrical terminals of the driving shell of the null transducer with respect to the voltage at the source projector until the output voltage at the outer shell is zero. Use the same signal generator to feed the source projector and the driving shell.

Place the hydrophone to be calibrated close to the geometric centre of the null transducer. For frequencies higher than 1 kHz, the calibration chamber shall be in accordance with 11.3.2.

When the simultaneous influences of the source projector and the driving shell of the null transducer neutralize one another, the deformation of the outer shell is zero; the sound pressure near the null transducer shall be then equal to:

$$p = K(d_{\mathrm{jk}}, E, r)U_{\mathrm{c}} \tag{44}$$

where

$K(d_{\mathrm{jk}}, E, r)$ is a characteristic constant of the piezoelectric null transducer;

d_{jk} is the piezoelectric modulus of the shell material;

E is the Young's modulus of the shell material;

r is the mean radius of driving transducer shell;

U_{c} is the compensation voltage at the frequency f.

The characteristic constant $K(d_{\mathrm{jk}}, E, r) = p/U_{\mathrm{c}}$ is generally independent of the frequency. It shall be determined experimentally by harmonically changing the water level over the null transducer with amplitude h_0 and compensating the resulting deformation of the null transducer by a compensation voltage with an amplitude ΔU_{c} at the null projector (see Figure 4). This compensation voltage shall have the same frequency as the oscillation of the water level. It shall be derived either from the oscillator that drives the variation of the water level, or from a pressure sensor that transforms the harmonic displacement of the water level into an alternating voltage.

NOTE 2 For this purpose, the cavity of the measuring tank is connected by means of a flexible tube with an open vessel, mounted on a shaker, producing vertical sinusoidal oscillations with a known amplitude. The oscillation frequency should be low enough (0,3 Hz) to permit neglect of the inertial forces arising in the vibrating liquid.

The amplitude ΔU_{c} of the compensation voltage and its phase shall be adjusted until the displacement of the null transducer is zero.

Then:

$$\begin{aligned} \Delta p &= \rho \mathrm{g}\, h_0 \\ K(d_{\mathrm{jk}}, E, r) &= \frac{\Delta p}{\Delta U_{\mathrm{c}}} = \frac{\rho \mathrm{g}\, h_0}{\Delta U_{\mathrm{c}}} \end{aligned} \tag{45}$$

where

Δp is the amplitude of the hydrostatic pressure oscillation;

h_0 is the amplitude of the water level oscillation;

ΔU_{c} is the amplitude of the compensation voltage.

The pressure sensitivity M_p of the hydrophone H in terms of the open-circuit voltage is equal to:

$$M_\mathrm{p} = \frac{U}{p} = \frac{U}{U_\mathrm{c}} \cdot \frac{\Delta U_\mathrm{c}}{\rho g h_0} \tag{46}$$

where U is the open circuit output voltage of the hydrophone H at a pressure p, dependent on the frequency. When the following conditions are met, the pressure sensitivity M_p is equal to the free-field sensitivity M_H:

a) the diffraction factor of the hydrophone is unity,

b) the hydrophone has negligible response to particle velocity and pressure gradient,

c) either the frequency of calibration is sufficiently below the lowest resonance frequency of the hydrophone so that the sensitivity of the hydrophone is independent of acoustic impedance or the apparent acoustic impedance of the hydrophone in the chamber is equal to the acoustic impedance in a free field.

This is assumed to be the case and M_H will be used in place of M_p for calibration using piezoelectric compensation.

11.3 Design of the calibration chamber

11.3.1 Low frequency chamber

The low-frequency chamber shall be constructed from a section of pipe fitted with lids on both ends. A source projector and null transducer shall be mounted on the lids (see Figure 4). The geometric centres of the transducers shall be located in the same horizontal plane.

The source projector shall produce a sufficiently high-pressure level to ensure a sufficient signal-to-noise ratio is obtained.

The following precautions shall be taken.

a) The tank shall be constructed in such a way that entrapped air can readily be removed.

b) The acoustic compliance of the tank walls shall be less than the compliance of the water volume.

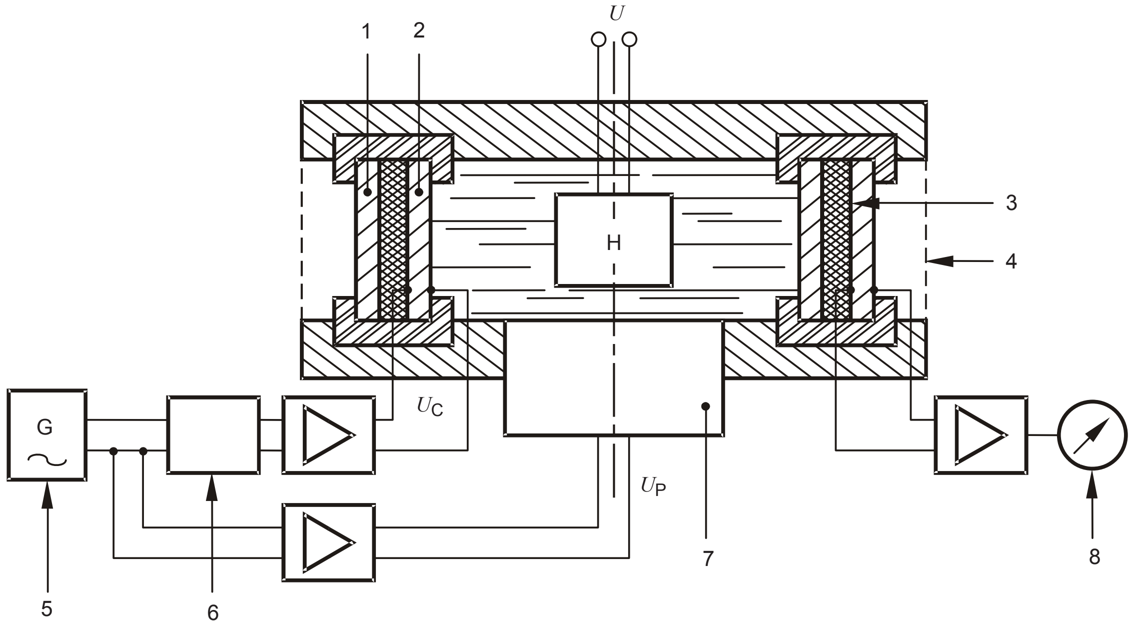
c) Tongue-and-groove or metal gasketting shall be used in preference to more compliant seals.

d) The tank shall be designed and the source projector mounted in such a way that excitation of flexural modes of vibration of the tank walls is minimized.

e) All necessary measures shall be taken to avoid the influence of any vibration of the tank on the null transducer and the hydrophone.

In order to control ambient conditions, the tank shall be equipped with facilities for degassing, circulating and pressurizing the water and for controlling its temperature. The hydrophone to be measured and the piezoelectric null transducer shall be installed as separate units.

11.3.2 High frequency chamber



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Key

1 Displacement sensor of the null transducer
2 Driving shell of the null transducer
3 Elastic filling substance
4 Shield
5 Signal generator
6 Phase and amplitude controls
7 Source projector
8 Null indicator

Figure 5 – Diagram of the chamber for high-frequency

The high frequency chamber shall be as shown in Figure 5. The linear dimensions shall be made as small as possible in order to increase the upper frequency limit to above 1 kHz.

The piezoelectric null transducer shall consist of two concentric cylindrical piezoelectric ceramic shells, clamped between two massive flanges. The space between the two cylinders shall be filled with an elastomeric, non-conducting material. The null transducer shall form the cylindrical wall of the chamber; and the measuring cavity of the chamber shall be not larger than the internal volume of the inner shell. The alternating pressure is generated by the source projector, a piezoelectric ceramic projector mounted in the bottom of the chamber. This projector shall produce a sufficiently high-pressure level to ensure enough excess of the measured signal over the noise.

Mount the hydrophone on the lid of the chamber. The same precautions shall be taken in the design of the high frequency chamber as those specified in 11.3.1 for the low frequency chamber. Moreover, precautions shall be taken to reduce the influence of the longitudinal deformation of the piezoelectric shells, caused by the transverse piezoelectric effect, on the output voltage of the deformation sensor. The null transducer and its electrical connections shall be adequately shielded.

11.4 Practical limitations of the piezoelectric compensation method

The method shall not be used at frequencies greater than the upper frequency limit, which is imposed by standing waves that may appear in the chamber at frequencies higher than 1 kHz. Standing waves cause a non-uniform pressure distribution in the chamber, so that the output level of the hydrophone depends on its position in the chamber.

Irrespective of the construction of the chamber, the system shall not be used at a frequency higher than about two-thirds of the fundamental resonance frequency of the tank cavity.

The method shall not be used at frequencies lower than the low-frequency limit, which is imposed by the loss of sensitivity of the piezoelectric deformation sensor caused by its own leakage resistance and the load resistance of the input of the null indicator.

NOTE 1 By proper design of the chamber, a frequency range from 1 Hz to 5 kHz can be covered by this method.

NOTE 2 If the hydrophone is symmetrical, it should be so arranged in the chamber that the planes of the acoustic symmetry of the null transducer and of the hydrophone coincide. In this way, the influence of standing waves on the calibration result is minimized and the frequency range can be extended. See [55].

NOTE 3 The plane of acoustic symmetry is the plane at which possible deviations of the sound pressure from the mean value, acting on different parts of the transducer, mutually compensate each other.

NOTE 4 In practice, the plane of the acoustic symmetry of the null transducer coincides with the plane of geometric symmetry. The same is true for a simple omnidirectional hydrophone if the areas of the active surface on opposite sides of the plane are equal, as well as the local sensitivities of these areas.

11.5 Uncertainty

The uncertainty in the calibration method shall be determined and stated with the value for the hydrophone sensitivity.

NOTE 1 If the conditions given in 11.3 are satisfied, the calibration by the piezoelectric compensation method is equivalent to a free-field calibration, with a possible overall expanded uncertainty of less than 1 dB (95 % confidence levels).

NOTE 2 At frequencies up to about one-fifth of the lowest resonance frequency of the chamber, the overall expanded uncertainty of the calibration can be less than 0,3 dB (95 % confidence levels).

12 Acoustic coupler reciprocity calibration

12.1 Principle

The primary calibration of hydrophones in a coupler using the reciprocity principle is undertaken. A method of absolute calibration of laboratory standard hydrophones with the highest obtainable accuracy is used. The frequency range of calibration of is generally restricted to frequencies between 0,1 Hz and 5 kHz [44], [59] to [61].

12.2 Procedure

A reciprocal transducer, a linear electro-acoustic sound source, and a hydrophone to be mounted in a fluid-filled coupler shall be used. The acoustical pressure sensitivity of the hydrophone shall be determined.

Using the reciprocal transducer as a projector and the hydrophone as a receiver, measure the magnitude of the electrical transfer impedance at a number of frequencies throughout the frequency range of interest.

NOTE See 7.5.

Using the sound source as a projector and alternately the reciprocal transducer and the hydrophone as receivers, measure electrical transfer impedances at the same set of frequencies as the above measurements.

From the three electrical transfer impedances measured at each frequency, the acoustical pressure sensitivity M_{p} of the hydrophone shall be calculated. The following conditions shall be met, so that the pressure sensitivity M_{p} is equal to the free-field sensitivity M_{H}:

a) the diffraction factor of the hydrophone is unity;

b) the hydrophone has negligible response to particle velocity and pressure gradient;

c) either the frequency of calibration is sufficiently below the lowest resonance frequency of the hydrophone so that the sensitivity of the hydrophone is independent of acoustic impedance or the apparent acoustic impedance of the hydrophone in the chamber is equal to the acoustic impedance in a free field.

This is assumed to be the case and M_{H} shall be used in place of M_{p} for acoustical reciprocity coupler calibration.

12.3 Theory

The arrangement of transducers in a coupler for reciprocity calibration shall be in accordance with Figure 6.

The theory for acoustical coupler reciprocity calibration shall follow that for free-field reciprocity calibration with the following substitutions:

a) Identify the quantity S_{Γ} with the small chamber transmitting response to pressure instead of the free-field response.

b) Substitute the reciprocity parameter for a small chamber ωC_{t} for the free-field reciprocity parameter at one metre $2/\rho f$ where C_{t} is the total acoustical compliance of the coupler.

c) Set $d = 1$ m in all free-field equations.

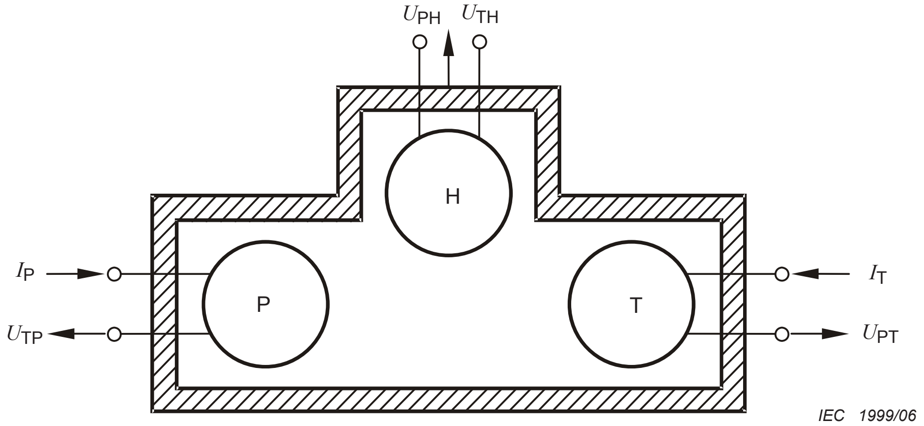

Figure 6 – Reciprocity coupler with three transducers; a projector P, a reciprocal transducer T, and a hydrophone H to be calibrated

$M_H{}^2$ shall be calculated from the following equation:

$$M_H^2 = \omega C_t \frac{|Z_{PH}||Z_{TH}|}{|Z_{PT}|} \tag{47}$$

where $|Z_{PH}|$, $|Z_{TH}|$, and $|Z_{PT}|$ are the magnitudes of the electrical transfer impedances as specified in 8.2.

12.4 Acoustic compliance

If the coupler and the transducers in the coupler are rigid and the volume V_f of the fluid in the coupler is accurately known, then the acoustical compliance shall be calculated by:

$$C_t = V_f / \rho_f c_f^2 \tag{48}$$

where ρ_f is the density of the fluid and c_f is the speed of sound in the fluid.

For the highest accuracy, the compliances of the coupler walls and the transducers in the coupler shall be taken into account. Resilient gaskets shall be designed in such a way that they are not exposed to the acoustical field in the coupler. The compliances of the active elements of the electro-acoustic transducers in the coupler shall either be calculated from published material properties or they shall be measured in the coupler using the method developed by McKinney et. al., see [62].

NOTE For the highest accuracy, the coupler wall compliance can be calculated using finite element methods.

Threaded components that support the internal pressure of the coupler using coarse, large threads shall be avoided since they do not provide a well-defined boundary condition.

12.5 High-frequency limit

The high-frequency limit shall be determined by the maximum interior dimension of the coupler. When this dimension exceeds one-tenth of the wavelength, the acoustical pressure in the coupler shall no longer be considered uniform and the calibration shall be no longer valid.

NOTE In some instances, it is possible to calculate the acoustical field within the coupler and correct for it, thus, raising the upper frequency limit. At 5 kHz, the maximum dimension for a coupler filled with water is 30 mm.

12.6 Low-frequency limit

The method shall not be used at frequencies below the low-frequency limit for the coupler.

NOTE There is no theoretical low frequency limit. In practice, however, the electrical problems in driving a small piezoelectric projector with very high electrical impedance mean that the practical lower limit should be 0,1 Hz for a coupler designed for use up to a few hundred hertz. A smaller coupler intended for use to higher frequency has low frequency limits that are correspondingly higher.

12.7 Measurement

Measurement shall be carried out in accordance with 7.3, 7.4, 8.6.5, 8.6.6 and 8.6.7.

12.8 Uncertainty

The reciprocity, linearity, and high-frequency limit conditions shall be satisfied as specified in 8.6.6, 8.6.7, and 12.5 and provided that equation (47) is valid, the overall expanded uncertainty (95 % confidence levels) of the calibration shall be less than 1 dB.

NOTE 1 The major contributors to the overall uncertainty are the uncertainty in the compliance of the coupler and the field non-uniformity within the coupler.

NOTE 2 By including all the contributions to the compliance of the coupler, by restricting the frequency of operation to even lower frequencies, and by calculating the effects of the acoustic field non-uniformity, the overall expanded uncertainty (95 % confidence levels) of the calibration can be reduced to less than 0,2 dB.

NOTE 3 If a hydrophone has a preamplifier, it is customary to place only the active element of the hydrophone in the coupler in order to keep the size of the coupler small. If the preamplifier housing of the hydrophone scatters sound, then the free-field sensitivity of the hydrophone will differ from the pressure sensitivity of the hydrophone. This is one possible cause of the diffraction factor differing from unity.

12.9 Limitations

The coupler shall not be used to calibrate hydrophones that are large, directional, or acoustically soft, or to calibrate hydrophones near resonance.

NOTE Hydrophones that can be calibrated in the reciprocity coupler shall be able to be mounted in a coupler in such a manner that they form a hard acoustic boundary within the coupler or their contribution to the compliance of the coupler shall be known. They shall also be designed in such a way that the interior volume of the coupler is known when they are mounted in the coupler. Few hydrophones meet these restrictions. In order to calibrate a more general population of hydrophones, it is necessary to extend the process by use of the techniques described in 12.10, 12.11, and 12.12.

12.10 Acoustic-coupler calibration using a reference coupler with two reciprocal transducers and an auxiliary coupler with the same two transducers and a hydrophone to be calibrated

12.10.1 Procedure

Place the two reciprocal transducers in a reference coupler whose volume and acoustic compliance are accurately known. Measure the electrical transfer impedance between one of the transducers used as a projector and the other transducer used as a hydrophone at a number of frequencies throughout the frequency range of interest.

Place the two reciprocal transducers in an auxiliary coupler along with the hydrophone to be calibrated. Measure the electrical transfer impedances between each of the transducers and the hydrophone and between each of the transducers and the other transducer used as a hydrophone at the same frequencies above.

From the five electrical transfer impedances measured at each frequency, calculate the acoustical pressure sensitivity of the hydrophone.

NOTE 1 The fill fluids in the two couplers need not be same.

NOTE 2 One coupler may serve both purposes if it is designed so that its properties are well known when the hydrophone is not present.

12.10.2 Theory

The arrangement for a reciprocity calibration shall be in accordance with Figure 7 and Figure 8.

NOTE 1 Figure 7 shows two transducers in a reference coupler, and Figure 8 shows three transducers in an auxiliary coupler.

Place two reciprocal transducers, T and P, and a hydrophone H in the auxiliary coupler. Denote all quantities that refer to the auxiliary coupler with primes. From equation (47), the hydrophone sensitivity shall be calculated by:

$$M_{\mathrm{H}}^{2} = \omega C'_{\mathrm{t}} \frac{\left|Z'_{\mathrm{PH}}\right|\left|Z'_{\mathrm{TH}}\right|}{\left|Z'_{\mathrm{PT}}\right|} \tag{49}$$

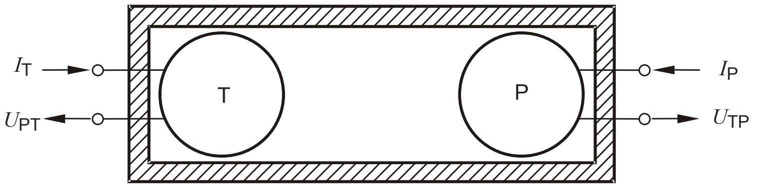

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Figure 7 – Reference coupler with two transducers: a projector P and a reciprocal transducer T

where, in this, C_{t}' is not known. To determine the electrical transfer impedance between the projector T as a sound source and the transducer P as a hydrophone, measure the electrical current I_{T}' into transducer T and the voltage U_{TP}'. The relationship between the input current and output voltage shall be:

$$U_{\mathrm{TP}}' = M_{\mathrm{P}} S_{\mathrm{T}}' I_{\mathrm{T}}' \tag{50}$$

where S_{T}' is the transmitting response to current of the transducer in the auxiliary coupler and M_{P} is the free-field sensitivity of the projector. From equation (50), the electrical transfer impedance Z_{TP}' shall be calculated by:

$$\left|Z'_{\mathrm{TP}}\right| = U_{\mathrm{TP}}' / I_{\mathrm{T}}' = M_{\mathrm{P}} S_{\mathrm{T}}' \tag{51}$$

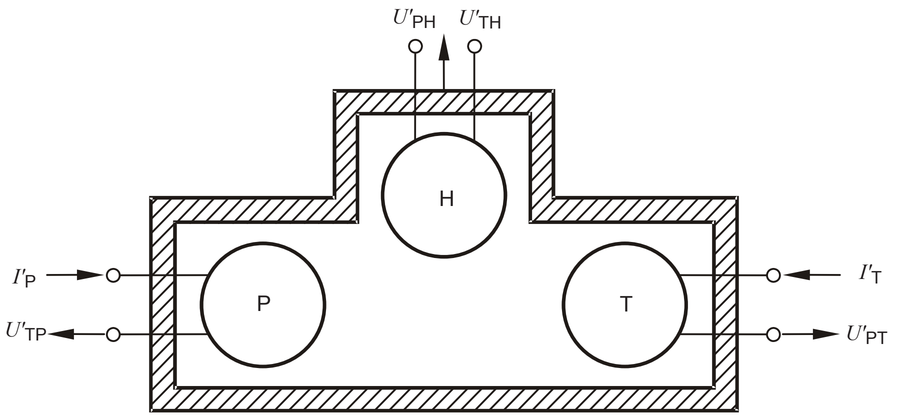

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Figure 8 – Auxiliary coupler with three transducers: a projector P, a reciprocal transducer T, and a hydrophone H to be calibrated

Since the transducer T is reciprocal, calculate:

$$S_{\mathrm{T}}' = \frac{M_{\mathrm{T}}}{\omega C_{\mathrm{t}}'} \qquad (52)$$

where M_{T} is the free-field sensitivity of the transducer.

Substitute equation (52) into equation (51) to yield:

$$\left|Z'_{\mathrm{TP}}\right| = \frac{M_{\mathrm{P}} M_{\mathrm{T}}}{\omega C_{\mathrm{t}}'} \qquad (53)$$

Now place the two reciprocal transducers in the reference coupler and measure the electrical transfer impedance between the projector T as a sound source and the transducer P as a hydrophone. In the same manner as above calculate:

$$\left|Z_{\mathrm{TP}}\right| = \frac{M_{\mathrm{P}} M_{\mathrm{T}}}{\omega C_{\mathrm{t}}} \qquad (54)$$

From equations (53) and (54), the relationship between the compliance in the auxiliary coupler and the compliance in the reference coupler shall be written as:

$$C_{\mathrm{t}}' = C_{\mathrm{t}} \frac{\left|Z_{\mathrm{TP}}\right|}{\left|Z'_{\mathrm{TP}}\right|} \qquad (55)$$

Substitute equation (55) into equation (49):

$$M_{\mathrm{H}}^{2} = \omega C_{\mathrm{t}} \left|Z_{\mathrm{TP}}\right| \frac{\left|Z'_{\mathrm{PH}}\right| \left|Z'_{\mathrm{TH}}\right|}{\left|Z'_{\mathrm{TP}}\right| \left|Z'_{\mathrm{PT}}\right|} \qquad (56)$$

NOTE 2 Using this method, ordinary small hard hydrophones may be calibrated with low uncertainty. The fill fluid in the auxiliary coupler can differ from that in the reference coupler. The compliance in the auxiliary coupler need not be known and is in effect, measured by measuring the electrical transfer impedance between the two reciprocal transducers in each of the two couplers.

12.11 Acoustic-coupler calibration using a reference coupler with two reciprocal transducers and an auxiliary coupler with the same two transducers, a hydrophone to be calibrated, and a sound source

12.11.1 Procedure

Place the two reciprocal transducers in a reference coupler whose volume and acoustic compliance are accurately known. Measure the electrical transfer impedance between one of the transducers used as a projector and the other transducer used as a hydrophone at a number of frequencies throughout the frequency range of interest.

Place the two reciprocal transducers in an auxiliary coupler along with the hydrophone to be calibrated and the sound source. Measure the electrical transfer impedance between the sound source and the hydrophone and between the sound source and each of the reciprocal transducers used as a hydrophone at the same frequencies as above.

From the four electrical transfer impedances measured at each frequency, calculate the acoustical pressure sensitivity of the hydrophone.

NOTE The fill fluids in the two couplers need not be the same.

12.11.2 Theory

NOTE 1 Figure 7 shows two transducers in the reference coupler and Figure 9 shows three transducers and a sound source in an auxiliary coupler.

The arrangement for a calibration shall be in accordance with Figure 7 and Figure 8.

The ratio $\left|Z'_{\mathrm{PH}}\right|/\left|Z'_{\mathrm{PT}}\right|$ shall be the ratio of voltages from the hydrophone H and the transducer T when subjected to the same sound pressure level produced by the projector P. This ratio shall be independent of the transducer used to produce the sound. If a sound source S produces the sound, calculate the following:

$$\left|Z'_{\mathrm{PH}}\right|/\left|Z'_{\mathrm{PT}}\right| = \left|Z'_{\mathrm{SH}}\right|/\left|Z'_{\mathrm{ST}}\right| \tag{57}$$

In a similar manner, the following calculation shall be carried out:

$$\left|Z'_{\mathrm{TH}}\right|/\left|Z'_{\mathrm{TP}}\right| = \left|Z'_{\mathrm{SH}}\right|/\left|Z'_{\mathrm{SP}}\right| \tag{58}$$

Substitute equations (57) and (58) into equation (56) to yield:

$$M_{\mathrm{H}}^{2} = \omega C_{\mathrm{t}}\left|Z_{\mathrm{TP}}\right|\frac{\left|Z'_{\mathrm{SH}}\right|\left|Z'_{\mathrm{SH}}\right|}{\left|Z'_{\mathrm{ST}}\right|\left|Z'_{\mathrm{SP}}\right|} \tag{59}$$

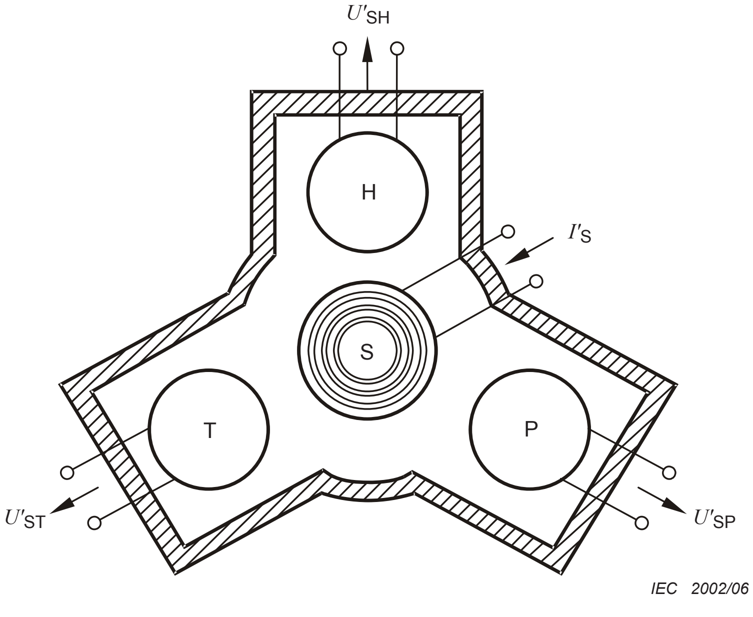


Figure 9 – Auxiliary coupler with four transducers; a projector P, a reciprocal transducer T, a sound source S, and a hydrophone H to be calibrated

NOTE 2 Using this method, ordinary small hard hydrophones may be calibrated to a high accuracy. The fill fluid in the auxiliary coupler can differ from that in the reference coupler. The compliance in the auxiliary coupler need not be known and is, in effect, measured by measuring the electrical transfer impedance between the two reciprocal transducers in each of the two couplers. Only the acoustical pressures at T, P, and H are required to be the same. Once the electrical transfer impedance $|Z_{\mathrm{TP}}|$ is measured, the transducer does not need to be used as a sound source again. This results in maximum stability for the transducer T.

12.12 Acoustic-coupler calibration using a coupler, a reciprocal transducer, a projector, a hydrophone to be calibrated, and a subsidiary body of known compliance

12.12.1 Procedure

A reciprocal transducer, a linear electro-acoustic sound source, a hydrophone and a subsidiary material of known compliance shall be used for the calibration. The hydrophone sensitivity shall be determined.

At first, do not place the subsidiary body in the coupler. Place the three transducers in the coupler and fill the coupler with a fluid (usually water). Using the reciprocal transducer as a projector and the hydrophone as a receiver, measure the magnitude of the electrical transfer impedance at a number of frequencies throughout the frequency range of interest (see 7.5).

Using the sound source as a projector and alternately the reciprocal transducer and the hydrophone as receivers, measure electrical transfer impedances at the same set of frequencies as the above measurements.

Place the subsidiary body in the coupler. Measure again the above three electrical transfer impedances.

From the six electrical transfer impedances measured at each frequency, calculate the acoustical pressure sensitivity of the hydrophone.

NOTE Knowledge of the coupler compliance is not needed.

12.12.2 Theory

The arrangement of the hydrophone, projector, transducer and subsidiary body shall be in accordance with Figure 10. This is an acoustic coupler and so shall be in accordance with 12.3 whether or not the subsidiary body is in the coupler [63].

NOTE 1 In this method, it is assumed that the acoustical compliance of the coupler without the subsidiary body is not known, but that the acoustical compliance of the subsidiary body is accurately known. In effect, the acoustical compliance of the coupler is determined from the acoustical compliance of the subsidiary body.

As in 12.3, calculate the free-field sensitivity of a hydrophone in a coupler without the subsidiary body by:

$$M_{\mathrm{H}}^{2} = \omega C_{\mathrm{t}} \frac{|Z_{\mathrm{PH}}||Z_{\mathrm{TH}}|}{|Z_{\mathrm{PT}}|} \equiv \omega C_{\mathrm{t}} Z_{\mathrm{eq}} \tag{60}$$

where the electrical transfer impedances $Z_{\mathrm{PH}}, Z_{\mathrm{TH}}$ and Z_{PT} shall be in accordance with 8.2 and where Z shall contain all the terms involving electrical transfer impedances.

Now, if the subsidiary body is placed in the coupler, the coupler compliance shall be calculated from $C_\mathrm{t} + \Delta C_\mathrm{t}$ where ΔC_t is given by:

$$\Delta C_\mathrm{t} = V_\mathrm{b}\left\{\frac{3(1-2\sigma)}{E} - \frac{1}{\rho_\mathrm{f}\ c_\mathrm{f}^2}\right\} \tag{61}$$

where

V_b is the volume of the subsidiary body;

E is Young's modulus for the subsidiary body;

σ is Poisson's modulus for the subsidiary body;

ρ_f is the density of coupler fluid; and

c_f is the speed of sound in the coupler fluid.

$3V_\mathrm{b}(1-2\sigma)/E$ is the acoustical compliance of the subsidiary body.

$V_\mathrm{b}/\rho_\mathrm{f}C_\mathrm{f}^2$ is the acoustical compliance of the fluid displaced by the subsidiary body.

$$M_\mathrm{H}^2 = \omega(C_\mathrm{t} + \Delta C_\mathrm{t})\frac{|Z'_\mathrm{PH}||Z'_\mathrm{TH}|}{|Z'_\mathrm{PT}|} \equiv \omega(C_\mathrm{t} + \Delta C_\mathrm{t})Z'_\mathrm{eq} \tag{62}$$

Eliminate C_t from the two expressions from M_H^2 to obtain:

$$M_\mathrm{H}^2 = \frac{Z_\mathrm{eq}\,Z'_\mathrm{eq}}{Z_\mathrm{eq} - Z'_\mathrm{eq}}\,\omega\Delta C_\mathrm{t} \tag{63}$$

The upper frequency limit for a given coupler size shall be increased using the following correction factor K_f^2 for equation (63):

$$K_\mathrm{f}^2 = \frac{\sin(kL)}{k\,L\cos(kz)\,\cos\left[k(L-z)\right]} \tag{64}$$

where

k is wave number;

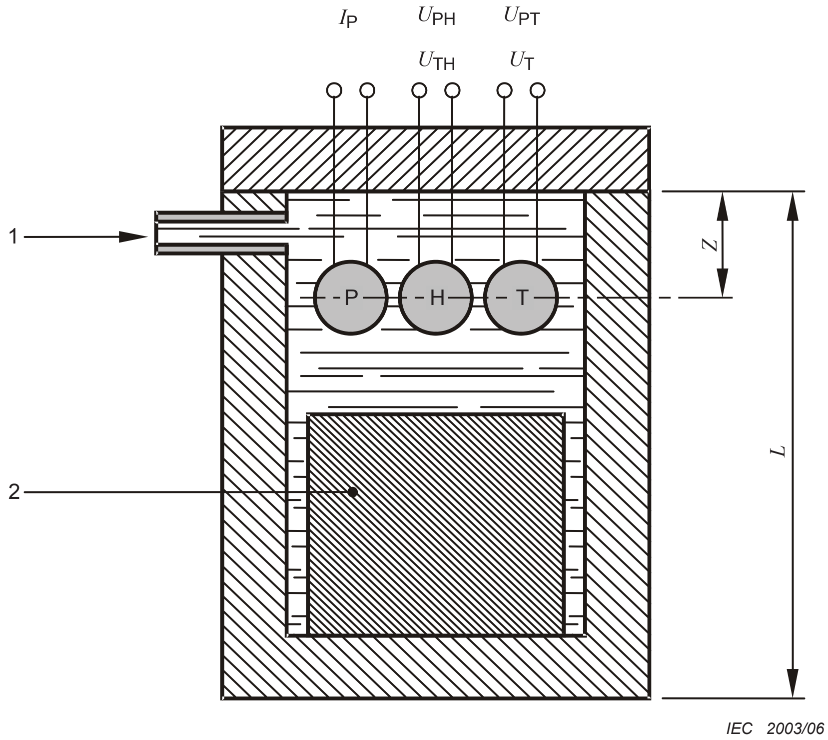
L is length of coupler;

z is distance from chamber lid to plane of the transducers (see Figure 10).

In this case, the corrected value of the pressure sensitivity of a hydrophone shall be calculated from:

$$(M_\mathrm{H})_\mathrm{cor} = K_\mathrm{f}M_\mathrm{H} \tag{65}$$

NOTE 2 For a chamber cavity of dimensions 175 mm (diameter) and 500 mm (length) the overall expanded uncertainty of the calibration (95 % confidence levels) can be less than 0,5 dB up to 500 Hz [57].



Key

1	Static pressure
2	Body of known compliance

Figure 10 – Schematic drawing of the measuring system.

NOTE 3 This method does not require knowledge of the compliance of the coupler which is usually difficult to determine accurately. It instead requires knowledge of the compliance of a subsidiary body and the fill fluid which can be determined accurately.

13 Calibration with a pistonphone

13.1 Principle

A hydrophone is calibrated at low frequencies inside a closed chamber, filled with air or partly filled with water. A simple method for calibration in a small chamber, without or with a standard transducer, is used, in the frequency range from a few hertz to several hundred hertz [1], [64].

NOTE This method may also be used for the calibration and performance checking of microphones [65] to [67].

13.2 Procedure

13.2.1 General

The calibration shall be performed in accordance with 13.2.2 or 13.2.3.

13.2.2 Absolute calibration

NOTE 1 In a pistonphone, the sound pressure is generated in a small closed air-filled chamber by a sinusoidally vibrating piston driven with a continuous wave signal. The piston may be driven by an electric motor or moving-coil transducer. The acoustic pressure p in the chamber shall be calculated from knowledge of the acoustic impedance, Z, and the volume velocity, u:

$$p = uZ \qquad (66)$$

NOTE 2 The sinusoidally varying volume velocity may be written in terms of the derivative of the volume displacement V_{D}.

Calculate the acoustic pressure p in the chamber using:

$$p = j\omega V_{\mathrm{D}} \frac{1}{j\omega C_{\mathrm{M}}} = \frac{V_{\mathrm{D}}}{C_{\mathrm{M}}} \tag{67}$$

where C_{M} is the compliance of the medium, and V_{D} is the volume displacement.

Clearly the sound pressure generated is independent of frequency and therefore shall be calculated from knowledge of V_{D} and C_{M}.

The volume displacement shall be calculated from the piston area and linear displacement if a means of measuring the displacement is available.

NOTE 3 This may be done using an optical interferometer.

If the piston does not behave as a perfect piston, its 'effective' area shall be used in the calculation of V_{D}.

Resonances of the medium and boundaries shall be at frequencies higher than the frequency range of interest and the acoustic impedance shall be purely a compliance.

NOTE 4 The compliance may be taken to be the compliance of only the medium since the compliance of the chamber boundaries, hydrophone and microphone are generally much smaller than the medium.

The compliance shall be calculated from the gas laws:

$$C_{\mathrm{M}} = \frac{V_0}{\gamma p_0} \tag{68}$$

where

V_0 is the total volume;

p_0 is the static pressure; and

γ is the ratio of specific heats for the gas.

NOTE 5 Corrections may need to be made to C_{M}, for example, to account for the heat conduction of the chamber walls.

A pistonphone shall be used to obtain an absolute calibration, and the pressure sensitivity of the hydrophone, M_{p}, shall be calculated from:

$$M_{\mathrm{p}} = \frac{U_{\mathrm{H}}}{p} \tag{69}$$

where U_{H} is the receive voltage generated by the hydrophone.

When the following conditions are met, the pressure sensitivity M_{p} shall be taken as equal to the free-field sensitivity M_{H}:

a) the diffraction factor of the hydrophone is unity;

b) the hydrophone has negligible response to particle velocity and pressure gradient;

c) either the frequency of calibration is sufficiently below the lowest resonance frequency of the hydrophone so that the sensitivity of the hydrophone is independent of acoustic impedance or the apparent acoustic impedance of the hydrophone in the chamber is equal to the acoustic impedance in a free field.

This shall be assumed to be the case and M_{H} shall be used in place of M_{p} for calibration using the pistonphone. From equations (67) to (69), the hydrophone sensitivity shall be calculated by:

$$M_{\mathrm{H}} = \frac{V_0 \, U_{\mathrm{H}}}{V_{\mathrm{D}} \, \gamma \, p_0} \tag{70}$$

13.2.3 Relative calibration

13.2.3.1 General

A relative calibration shall be carried out in accordance with 13.2.3.2 or 13.2.3.3.

13.2.3.2 Calibrated reference transducer

A relative calibration shall be obtained by inserting a calibrated reference transducer into the chamber along with the device under test. Here the pistonphone shall be used to provide a stable sound pressure to enable the comparison calibration to take place.

NOTE 1 This has the advantage that the volume displacement and compliance do not need to be calculated.

The reference device used shall be a calibrated microphone. The sensitivity of the hydrophone shall be calculated from:

$$M_{\mathrm{H}} = \frac{U_{\mathrm{H}}}{U_{\mathrm{M}}} M_{\mathrm{M}} \tag{71}$$

where U_{M} and M_{M} are the receive voltage and sensitivity of the microphone.

Both the hydrophone and the microphone shall be simultaneously inserted into the coupler and exposed to the same acoustic pressure rather than using a substitute procedure.

NOTE 2 This ensures that the volume of the coupler does not change between measurements.

The chamber dimensions shall be small in comparison to the acoustic wavelength. Under such conditions, and if the chamber is rigidly bounded, the sound pressure may be regarded as constant throughout the chamber at low frequencies.

13.2.3.3 Air-water pistophone

The piston shall be used to drive a small air cavity above the water and the sound pressure shall be the same in both air and water. A microphone shall be used to monitor the pressure in the air cavity. Either a comparison calibration between two hydrophones shall be performed or an absolute calibration shall be attempted [1], [64].

NOTE 1 Figure 11 shows a schematic diagram of an air-water pistonphone used for a comparison calibration between two hydrophones.

NOTE 2 An air-water pistonphone has the advantage that due to the greater sound speed (and consequent larger wavelengths) in the water medium, the frequency at which the pressure is no longer uniform is increased. Care should be taken to keep the chamber design simple and symmetric to achieve a uniform acoustic pressure over the largest frequency range.

NOTE 3 A completely water-filled pistonphone has also been used [1]. However, unlike the case of an air medium, here the compliance of the boundaries may no longer be small compared with that of the water (the hydrophone boot, cable and boundary walls may all contribute) requiring the compliance to be measured during each calibration.

13.3 Limitations

The method shall not be used at frequencies greater than the upper limiting frequency caused by non-uniform acoustic pressure in the chamber. For the assumption of uniform pressure to hold, the chamber shall have a largest dimension of no more than one sixteenth of the wavelength (which is equivalent to about 70 mm for an air-filled chamber which operates up to 300 Hz).

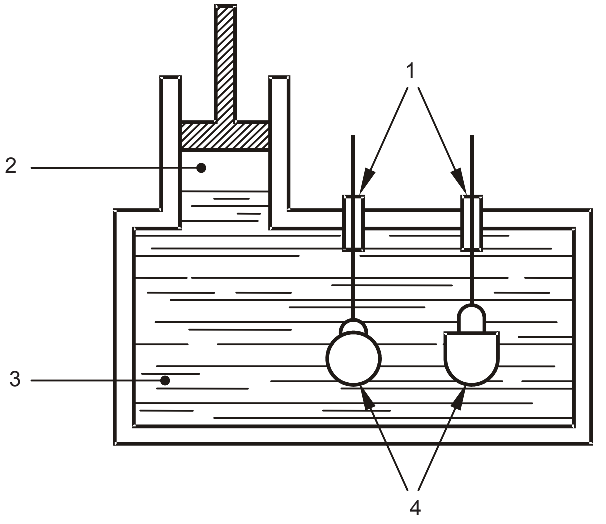
NOTE 1 As the frequency increases, the pressure will become non-uniform as wave modes begin to become evident in the chamber. If the chamber is of simple geometry, corrections may be made for these wave modes, but the uncertainty on the corrections will increase with frequency. This will in general pose a limit on the upper frequency of operation that will depend on the size of the chamber. For typical chamber sizes, this will be of the order of 300 Hz to 500 Hz.

NOTE 2 Non-uniform pressure will lead to errors in an absolute calibration since the acoustic pressure at the hydrophone may not be that calculated from the piston volume velocity and chamber compliance. In the case of a comparison calibration, the hydrophone and reference microphone/hydrophone may not experience the same acoustic pressure.

The method shall not be used at frequencies lower than the lower limiting frequency caused by thermal conduction between the air and the chamber walls and air leakage around the piston.

NOTE 3 Departure from purely adiabatic conditions may occur at low frequencies due to thermal conduction between the air and the chamber walls. The effect is small in general, but it increases as the frequency decreases. At frequencies greater than 5 Hz, the effect is negligible.

NOTE 4 Air leakage around the piston depends upon the radial clearance between the piston and the bore. If this clearance is of the order of a few hundredths of a millimetre, any effect will be negligible for frequencies greater than 5 Hz.



IEC 2004/06

Key

1 Bulkhead feed-throughs

2 Air

3 Water

4 Hydrophones

Figure 11 – Pistonphone

13.4 Uncertainty

The overall uncertainty shall be evaluated and stated with the hydrophone sensitivity. If the conditions specified in 13.1, 13.2 and 13.3 are satisfied, the overall expanded uncertainty (95 % confidence levels) of the calibration shall be less than 0,5 dB.

NOTE 1 For comparison calibration using the pistonphone, the uncertainty will in general be higher. With good practice it can be less than 1,0 dB (95 % confidence levels).

NOTE 2 The following will contribute to sources of uncertainty in absolute calibrations using a pistonphone: measurement of the piston displacement amplitude; measurement of the effective area of the piston; measurement of the equilibrium air volume of the chamber; measurement of the equilibrium air pressure in the chamber.

NOTE 3 The following will contribute to sources of uncertainty in relative calibrations using a pistonphone: uncertainties in the calibration of the reference microphone or hydrophone.

NOTE 4 The following will contribute to sources of uncertainty in both methods: uncertainty in electrical measurements made by equipment such as voltmeters (may be reduced if both voltages are measured using same equipment); the gain of any hydrophone amplifiers used; lack of uniform acoustic pressure in the chamber (high frequencies); thermal conduction between air and chamber walls (low frequencies); air leakage around piston (low frequencies).

14 Calibration with a vibrating column

14.1 Principle

A simple method for calibration of a hydrophone in an open chamber is carried out, without a standard transducer, in the frequency range from 10 Hz to 1 kHz. This method, uses an open column of liquid at low frequencies at which the wavelength is larger than the length of the column, allowing a hydrophone to be calibrated in a simple way [1], [67].

14.2 Procedure

Immerse a hydrophone in a column of liquid, which is excited externally by a sinusoidal vibration, while the hydrophone is held fixed and vertically suspended near to the central axis of the column.

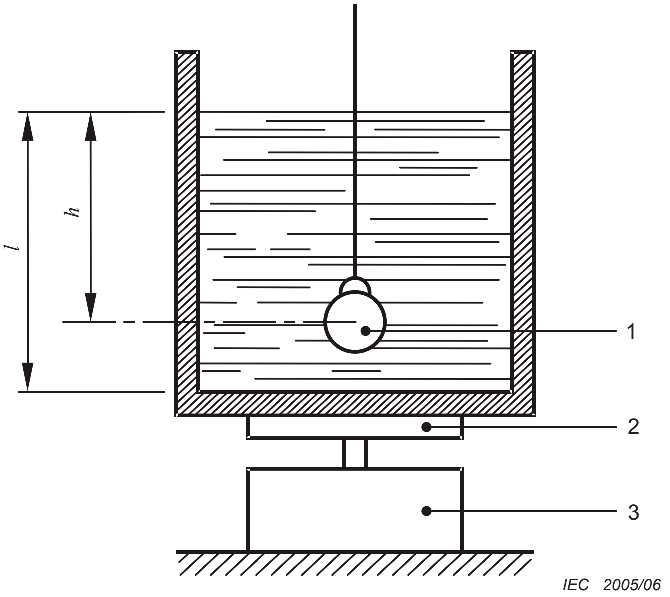
The column of liquid shall be contained in a cylindrical vessel with rigid walls. Within this vessel, open at the top, the liquid column shall either be driven at the bottom by an electrodynamic transducer, or the whole vessel shall be driven by a vibrating generator, in accordance with Figure 12.

The sensitivity of the hydrophone shall be obtained from the calculated pressure at the depth of the hydrophone and the measured open circuit voltage.

NOTE 1 This method is an absolute calibration, although it lends itself to calibration by separated comparison as well. See 13.2.

The upper limit of the useful frequency range depends on the size of the vessel, which shall be smaller than a quarter of the wavelength of the sound in the liquid, see 14.5.1.

NOTE 2 Generally a frequency range from 10 Hz to 1 kHz can be used.



Key

1 Hydrophone

2 Piston

3 Vibration generator

Figure 12 – Vibrating column

14.3 Expression for the pressure

Supposing that all parts of the liquid move equally with respect to their equilibrium position, the peak amplitude $\hat{p}$ of the oscillating pressure at a point in the liquid at a depth of h below the surface shall be calculated by:

$$\hat{p} = \rho\, \hat{x} \left| \mathrm{g} - h\omega^2 \right| \tag{72}$$

where

ρ is the density of the liquid;

$\hat{x}$ is the peak amplitude of the vibration of the bottom of the vessel;

g is the acceleration due to gravity; and

ω is the angular frequency of the vibration.

NOTE Pressure fluctuations due to the flow of the liquid past the hydrophone are disregarded in this equation. These fluctuations are small compared with the signal pressure when the hydrophone is small compared with the depth of immersion and when the vibration amplitude is small compared with the size of the hydrophone. See [63].

At very low frequencies, where $h\omega^2$ is small compared with g, equation (72) shall be reduced to:

$$\hat{p} = \rho\, \mathrm{g}\, \hat{x} \tag{73}$$

which is independent of the frequency.

At higher frequencies, when $h\omega^2$ becomes large compared with g, the pressure shall be proportional to the square of the frequency:

$$\hat{p} = \rho\, \hat{x}\, h\, \omega^2 \tag{74}$$

The change-over shall be considered to take place at an angular frequency:

$$\omega_\mathrm{o} = \sqrt{\frac{\mathrm{g}}{h}} \tag{75}$$

which, for example, corresponds to the frequency 1,6 Hz when h = 10 cm.

Hence, equation (74) shall be practically valid at frequencies higher than 10 Hz.

14.4 Determination of the sensitivity

The pressure sensitivity of the hydrophone M_p shall be calculated as the ratio of the peak values of the open circuit voltage $\hat{U}$ and the pressure $\hat{p}$, as given by equations (72), (73) or (74):

$$M_\mathrm{p} = \frac{\hat{U}}{\hat{p}} \tag{76}$$

When the following conditions are met, the pressure sensitivity M_p shall be equal to the free-field sensitivity M_H:

a) the diffraction constant of the hydrophone is unity;

b) the hydrophone has negligible response to particle velocity and pressure gradient;

c) either the frequency of calibration is sufficiently below the lowest resonance frequency of the hydrophone so that the sensitivity of the hydrophone is independent from acoustic impedance or the apparent acoustic impedance of the hydrophone in the chamber is equal to the acoustic impedance in a free field.

This is assumed to be the case and M_H shall be used in place of M_p for calibration with a vibrating column.

The calibration shall be performed under the conditions specified in Clauses 6 and 7.

The peak value of the open-circuit voltage at the electrical terminals of the hydrophone shall be measured in accordance with 7.3.

For the determination of the peak value of the pressure, either the peak amplitude of the vibration $\hat{x}$ at the bottom of the vessel or the peak value of the acceleration $\hat{x}\,\omega^2$ shall be measured.

The uncertainty in the results of these measurements shall be less than 1 % (95 % confidence levels).

The acceleration shall be measured by means of an accelerometer at the bottom of the vessel.

The depth of immersion h shall either be measured at the reference centre of the part of the hydrophone designed to receive sound, see **3.3,** or the value of h shall be eliminated from the equation by repetition of the measurement at two different depths h_1 and h_2. The peak values of the output voltages at the hydrophone shall be respectively $\hat{U}_1$ and $\hat{U}_2$.

Then, if

$$\Delta\hat{U} = \hat{U}_1 - \hat{U}_2 \tag{77}$$

and

$$\Delta h = h_1 - h_2 \tag{78}$$

equations (74) and (76) shall give either:

$$\Delta\hat{U} = M_H \rho\, \hat{x}\, \omega^2 \Delta h \tag{79}$$

or

$$M_\mathrm{H} = \frac{\Delta\hat{U}}{\Delta h}\frac{1}{\rho\,\hat{x}\,\omega^2} \tag{80}$$

NOTE In equation (80), the absolute value of the immersion depth is eliminated and replaced by the difference between the immersion depths for two measurements. This difference can be established without knowledge of the location of the acoustic centre of the hydrophone.

The depth difference shall be measured with an uncertainty of less than 1 %.

14.5 Conditions of measurement

14.5.1 Mechanical

The hydrophone's suspension shall be designed not to vibrate, neither by mechanical contact with the vessel, nor by viscous drag of the liquid. In order to avoid corrections for the hydrodynamic flow of the liquid past the hydrophone, the diameter of the column shall be large compared with the diameter of the hydrophone. For the same reason, the amplitude of the vibration shall be small compared with the size of the hydrophone.

The stiffness of the vessel shall be sufficiently high that the lowest resonance frequency of the empty vessel is higher than the lowest resonance frequency of the liquid column.

The length of the column shall be larger than its diameter.

NOTE 1 The lowest resonance frequency of such an open column of liquid occurs when the length of the column equals a quarter of the wavelength. When the frequency is lower than a quarter of this resonance frequency, the required correction is less than 1 dB.

For this condition $\left(\ell \leq \frac{1}{4} \cdot \frac{\lambda}{4}\right)$ the length of the column shall not be larger than one-sixteenth of the wavelength of the sound in the liquid [63].

At higher frequencies, the sound pressure in the column shall be given by the following equation:

$$\hat{p} = \rho\, \hat{x}\, \omega^2\, h \frac{\sin\left(\frac{\omega h}{c}\right)}{\left(\frac{\omega h}{c}\right)\cos\left(\frac{\omega \ell}{c}\right)} \qquad (81)$$

where

c is the speed of sound in the liquid column, taking into account the compliance of the walls of the vessel; and

ℓ is the length of the column.

NOTE 2 This equation may be applied only if ℓ is smaller than a quarter of the acoustic wavelength in the liquid.

NOTE 3 At low frequencies, the trigonometric fraction in this equation approaches unity, giving equation (74).

14.5.2 Acoustical

In order to make sure that the pure pressure sensitivity of the hydrophone is measured, the acoustic impedance presented by the hydrophone shall be large compared with the acoustic impedance of the liquid column. The latter value depends on the depth h and shall be in accordance with the equation for the specific acoustic impedance Z:

$$Z = j\, \rho\, c \tan\frac{\omega h}{c} \qquad (82)$$

This value shall be zero at the surface and shall increase to infinity at a depth of a quarter of the wavelength. But, because the upper limit of the useful frequency range occurs where the total length of the column equals a quarter wavelength, the hydrophone shall never be placed at a point in the column where the specific acoustic impedance is infinitely high.

NOTE 1 Hence, near to the surface no hydrophone, not even the more compliant types, will disturb the sound field, provided that the hydrophone is small compared with the diameter of the column. At greater depth, a point may be reached where the acoustic impedance magnitude of the column becomes higher than the acoustic impedance magnitude of the hydrophone. From this point, at greater depths of immersion, the measured sensitivity of the hydrophone seems to decrease with depth. This can be verified by performing the calibration at various depths.

NOTE 2 Taking into account the pressure distribution given in equation (81), the sensitivity of the hydrophone should not change with depth.

If, however, the sensitivity changes due to the relation between the acoustic impedance of the hydrophone and of the water column, the possibility of errors in the calibration shall be considered, see Annex E.

14.6 Uncertainty

The overall uncertainty shall be evaluated and stated with the hydrophone sensitivity. Provided that the condition $\ell \leq \lambda / 16$ is met, the pressure is given by equation (74), and that the density ρ of the liquid, the peak acceleration at the bottom of the vessel $\hat{x}\,\omega^2$, the depth h and the peak output voltage $\hat{U}$ are measured with an uncertainty of less than 1 %, the overall expanded uncertainty shall be less than 1 dB (95 % confidence levels).

NOTE Provided that equation (74) is used for the pressure, the uncertainties in the speed of sound, the length of the column ℓ and the depth of the hydrophone will influence the overall uncertainty of the final results.

Annex A
(informative)

Directional response of a hydrophone

A.1 Procedure

A complete determination of the characteristics of a hydrophone should include a measurement of its directional response at representative frequencies above the range where it is still omnidirectional (see 3.18).

The accuracy of the directional response measurement is affected by the same quantities that limit the accuracy of the sensitivity measurement, together with some additional requirements. A larger separation distance is generally required. (See 8.3 and C.2.2) The signal level attributable to reflections and noise generally should be lower than for measurement of sensitivity of the principal axis (see 3.23) because of the low level of the signals to be measured at some directions off the axis.

If the reference centre (see 3.25) is not on the axis of rotation, errors in the phase and the amplitude of the measured directional response may arise, caused by the varying separation distance and parallax. The transducer should be rotated slowly enough for the recorder to respond accurately to the maximum rate of change in the signal level that may occur around the null directions of the directivity pattern.

In general, uncertainties in the patterns in the region of maximum response can be expected to be about 0,5 dB (95 % confidence levels). In addition, an uncertainty of 1 dB for each angular deviation loss between 10 dB and 30 dB can be expected. When the uncertainty is substantially different from these values, the magnitude and source of the uncertainty should be stated.

A.2 Graphic representation

A directional response pattern usually is presented in the form of a two dimensional polar graph (see IEC 60263:1982). The scale of the polar graph may be in terms of sensitivity level or in angular deviation loss. Each directional response pattern should be identified as to type of pattern, frequency or frequency band, pattern orientation within the specified co-ordinate system, and the ambient conditions upon which the pattern depends, such as temperature, pressure or depth of immersion, speed of sound and distance. The angular scale for a pattern in the XY-plane is expressed as the azimuth angle φ. The pattern in the YZ-plane, expressed as θ, should indicate the direction of the positive Y-axis, and, similarly for the pattern in the XZ-plane, the direction of the positive X-axis should be shown, unless the pattern in the XY-plane is omnidirectional, thus a circle.

A.3 Directivity factor

The directivity factor (R_θ) (IEV 801-25-67) can be expressed as:

$$R_\theta = \frac{4\pi d^2 p_a^2}{\int_{Sphere} p^2(\theta,\varphi)\, dS} = 4\pi \left\{ \int_0^{2\pi} \int_0^{\pi} \left(\frac{p(\theta,\varphi)}{p_a} \right)^2 \sin\theta \,\mathrm{d}\theta\, \mathrm{d}\varphi \right\}^{-1} \quad \text{(A.1)}$$

where

$p(\theta,\varphi)$ is the sound pressure as a function of the direction at some fixed distance d;

p_a is the sound pressure in the reference direction for R_θ, at the same distance d;

d is the radius of the sphere whose centre is the reference centre of the hydrophone (see 3.25);

$\mathrm{d}S$ is the differential element of area on the surface of the sphere.

This equation refers to the emission of sound by the transducer.

For sound reception, $p(\theta,\varphi)$ and p_a are replaced by the open-circuit voltage of the hydrophone as a function of the direction of the impinging sound wave.

The equation can be evaluated from directivity patterns by the use of special plotters and a planimeter (see [5]). If the polar plots indicate that the hydrophone closely represents either a piston in an infinite baffle, or a line, then theoretical values of the directivity factor may be used [4], [6] and [7].

A.4 Directivity index

According to IEV 801-25-68, the directivity index is equal to:

$$D_i = 10 \log R_\theta \quad \text{(A.2)}$$

NOTE For formulae, charts and graphs of D_i for some types of hydrophones, see [1] and [4].

Annex B
(informative)

Electrical loading corrections

B.1 Electrical loading corrections

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

B.2 Corrections using complex electrical impedance

Consider the general case in which the hydrophone is considered as a two-terminal network of complex electrical impedance Z_{H} connected to an electrical load of complex electrical impedance Z_{L}. The end-of-cable loaded sensitivity of the hydrophone, M_{L}, when connected to the specified load is related to the end-of-cable open-circuit sensitivity, M_0, by [12]:

$$M_{\mathrm{L}} = M_0 \sqrt{\frac{Re\left(Z_{\mathrm{L}}\right)^2 + Im\left(Z_{\mathrm{L}}\right)^2}{[Re\left(Z_{\mathrm{L}}\right) + Re\left(Z_{\mathrm{H}}\right)]^2 + [Im\left(Z_{\mathrm{L}}\right) + Im\left(Z_{\mathrm{H}}\right)]^2}} \tag{B.1}$$

where $Re(\ )$ and $Im(\ )$ denote the real and imaginary parts of the relevant complex electrical impedance.

Often, the electrical load can be assumed to be a parallel combination of a resistance R_{L} and capacitance C_{L}. In this case, $Re\left(Z_{\mathrm{L}}\right)$ and $Im\left(Z_{\mathrm{L}}\right)$ are given by:

$$Re\left(Z_{\mathrm{L}}\right) = \frac{R_{\mathrm{L}}}{1 + \omega^2 C_{\mathrm{L}}^2 R_{\mathrm{L}}^2} \tag{B.2}$$

and

$$Im\left(Z_{\mathrm{L}}\right) = \frac{-\omega C_{\mathrm{L}} R_{\mathrm{L}}^2}{1 + \omega^2 C_{\mathrm{L}}^2 R_{\mathrm{L}}^2} \tag{B.3}$$

where ω is the angular frequency.

B.3 Corrections using only capacitances

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

$$M_\mathrm{L} = M_0 \left[\frac{C_\mathrm{H}}{C_\mathrm{H} + C_\mathrm{L}} \right] \tag{B.4}$$

Annex C
(informative)

Pulsed techniques in free-field calibrations

C.1 General

To achieve a free-field environment for the calibration of underwater electroacoustic transducers, the measurements should be made in the absence of acoustic reflections from the boundaries of the medium. This may be achieved by use of a facility based on a large volume of water such as a lake or reservoir, or during trials at sea. In such cases, the reflections are often sufficiently attenuated by propagation losses and by absorption at the boundaries that continuous wave signals may be employed. However, such facilities have disadvantages such as lack of environmental control, logistical difficulties in deployment, and relatively high financial cost [1].

The disadvantages of using large volumes of water have led to the use of laboratory tanks for calibration. Such facilities provide controlled environments for test and calibration of transducers and enable suitable rigging and mounting for the transducers to be incorporated into the facility at more affordable cost. However, to use finite-sized tanks, a means should be found to eliminate the effect of boundary echoes (or at least to control or limit their influence). One method is to coat the boundaries with absorbers. However, effective absorbers for underwater sound are expensive and rarely provide sufficient broadband absorption at low kilohertz frequencies. Nevertheless, absorbers are useful in reducing the overall reverberation time of the tank, allowing faster signal repetition rates.

The most common method of achieving a free-field environment for calibration is to use electronic gating techniques to gate the transmitted and received signals. The direct path signal may then be isolated in the time-domain before the arrival of boundary reflections (which undergo a longer propagation path and arrive later in time). A suitable time interval is necessary between the transmission of successive pulses to allow any reverberation to die away [69].

Typically, bursts of single frequency sound are used as the signal type. The signal may be generated using a sinusoidal oscillator and an electronic gating unit, or using a function generator that will generate a ‘tone-burst’ signal directly. This signal is then swept through discrete frequencies to provide each of the required frequencies for measurement.

Other broadband signal types may be used to provide great frequency coverage within each pulse, but these will usually result in a degraded signal-to-noise ratio at the frequencies of measurement.

C.2 Considerations

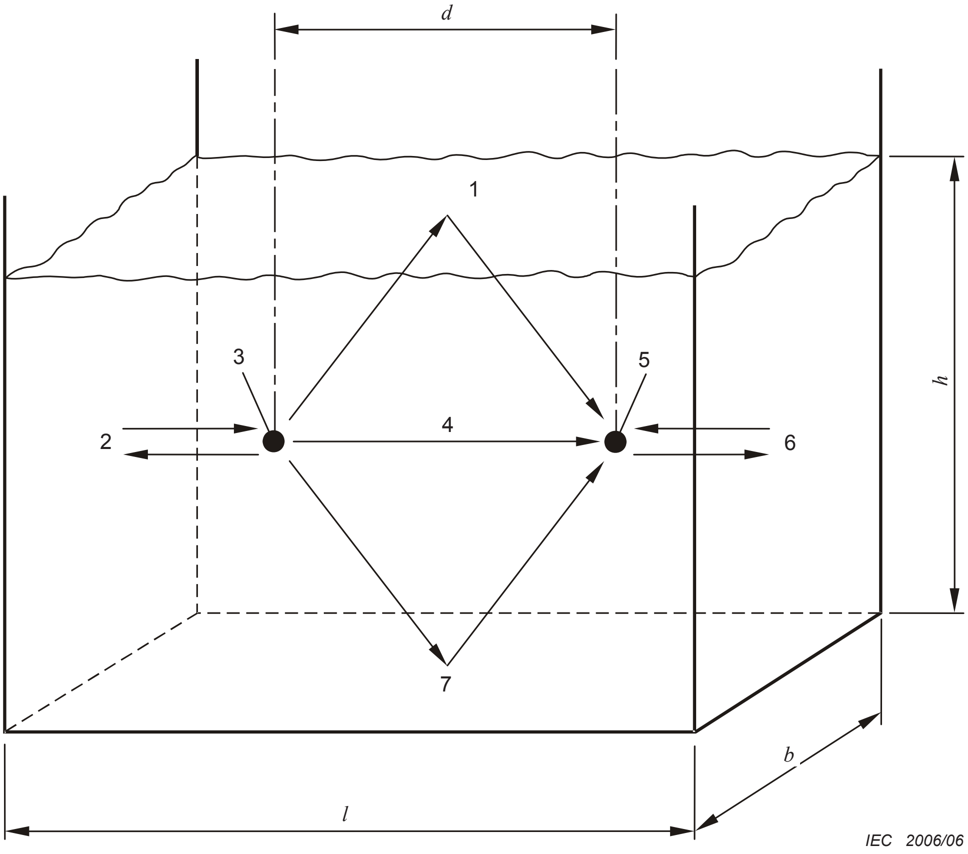
C.2.1 Echo-free time

In Figure C.1, a schematic is shown of two transducers in a rectangular cross-sectioned laboratory tank illustrating the sources of echoes from the boundaries. By simple geometrical considerations (and knowing the speed of sound in water), it is possible to calculate the arrival time of the echoes and therefore the amount of time-domain signal available for analysis before the arrival of echoes, the 'echo-free time'.

Note that in the example, the transducers are optimally positioned on a central axis of the tank to give the greatest time delay between the direct path arrival and the arrival of the boundary echoes. However, the amount of echo-free time will depend upon the separation distance chosen.

Ignoring multiple reflections, if the arrival time of the N^{th} boundary echo relative to the direct path arrival is denoted by T_N and the speed of sound is c, then the following relationships should be satisfied:

$$T_1 = \frac{l - d}{c}; \quad T_2 = \frac{2d}{c}; \quad T_3 = \frac{\sqrt{b^2 + d^2} - d}{c}; \quad T_4 = \frac{\sqrt{h^2 + d^2} - d}{c} \tag{C.1}$$



Key

1	Surface reflection
2	Back wall reflection
3	Transmitter
4	Direct signal
5	Receiver
6	Far wall reflection
7	Bottom reflection

Figure C.1 – Schematic diagram of a projector and receiver in a water tank showing the main sources of reflections

The first relationship concerns reflections from the end walls of the tank, the second relates to reflections between transducers, the third relates to reflections from the side walls of the tank, and finally the fourth relates to the reflections from the bottom and water surface. These formulae have been plotted in Figure C.2 for the example of a tank that is 6 m long by 6 m wide by 5 m deep.

For the measurements to be made in the absence of boundary reflections at a chosen separation distance, the duration of the transmitted pulse cannot exceed the values given by the lowest-valued curve shown on Figure C.2. For example, at a separation of 2 m, the echo-free time in this tank is approximately 2,25 ms [1], [2], [12], [38] and [69].

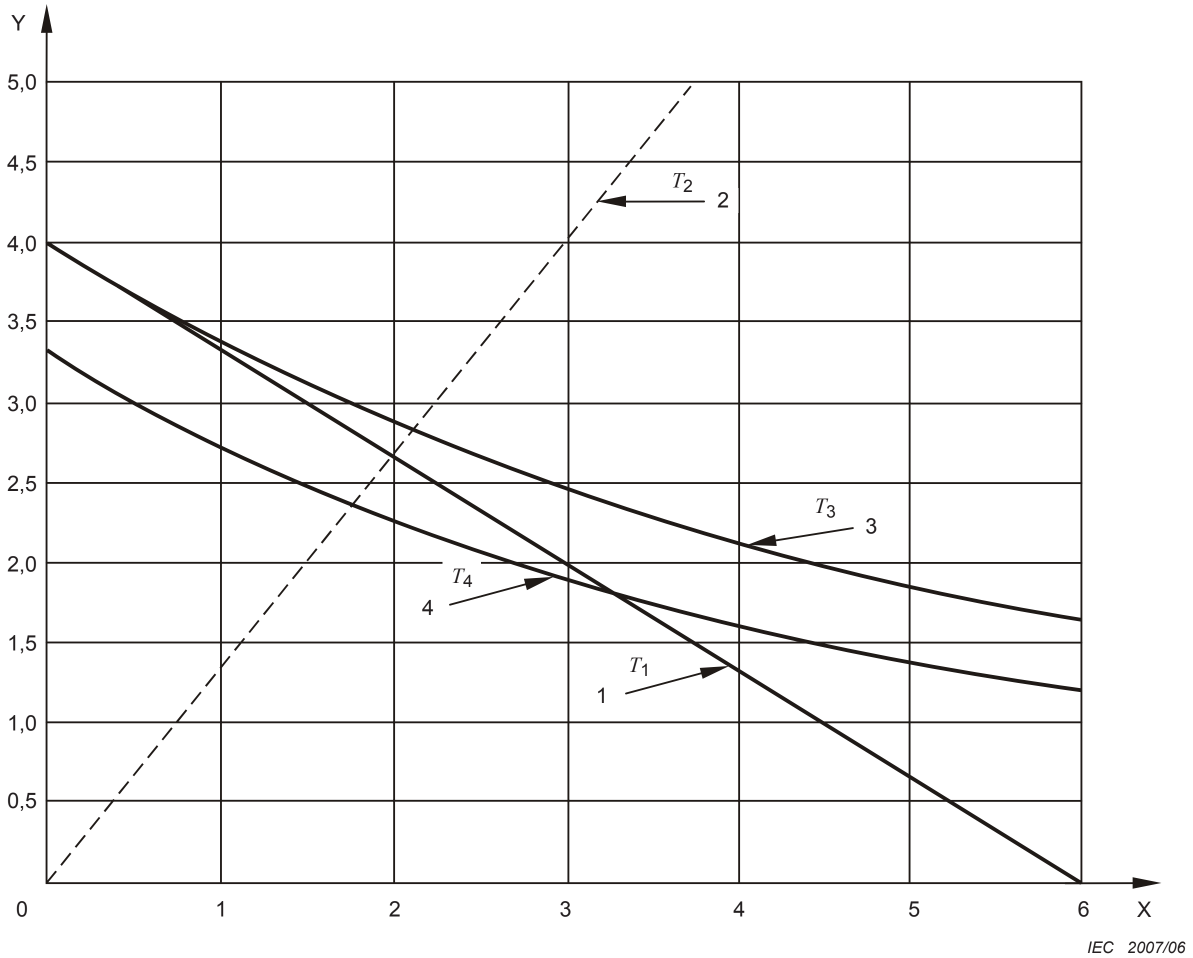
C.2.2 Minimum separation distance

An additional factor which should be taken into account is the minimum separation distance required to achieve acceptable far-field conditions, given by:

$$d > \frac{a_1^{\,2} + a_2^{\,2} + a_1 a_2}{\lambda}; \quad d > 5a_1 \quad \text{and} \quad d > 5a_2 \tag{C.2}$$

where λ is the wavelength at the highest frequency of measurement. This provides a limit on the minimum separation distance between the transducers.

For measurement of directional responses, the minimum separation distance requirements are more stringent and a distance of at least twice the above minimum is recommended, see 8.3 [41], [42].



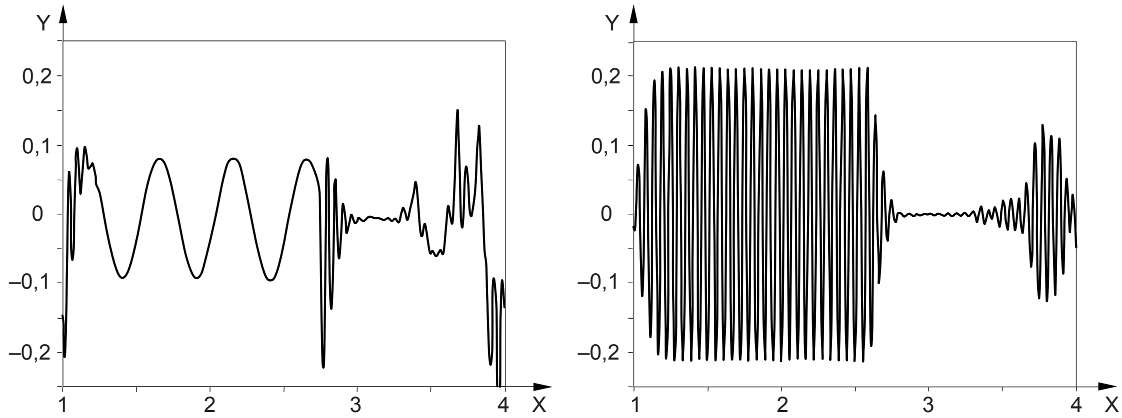
Key

1	End wall reflections
2	Reflections between transducers
3	Side wall reflection
4	Surface and bottom reflections
X	Separation in metres
Y	Echo arrival time in milliseconds

Figure C.2 – Echo arrival time in a 6 m × 6 m × 5 m tank with optimally placed transducers

C.2.3 Turn-on transients

In addition to reflections of the transmitted signal from the tank walls and floor, and the water surface, the hydrophone signal is also contaminated by transients due to the resonant behaviour of the devices. From the sampled signal, an estimate of the steady-state amplitude of the hydrophone signal is required. Figure C.3 shows typical examples of hydrophone signals measured during a calibration showing the turn-on transients, steady-state region and the arrival of the first reflections. At low frequencies, there are fewer complete cycles of the transmitted signal within the steady-state region. Consequently, direct measurement of the steady state portion of the received signal is less reliable, and ultimately this imposes a lower bound on the range of frequencies over which hydrophones may be calibrated.



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Key

X Time (milliseconds)

Y Voltage (volts)

Figure C.3 – Hydrophone signals for a pair of spherical transducers (projector: 18 kHz resonance frequency, Q factor of 3,5; hydrophone: 350 kHz resonance frequency; drive frequency: 2 kHz (left) and 18 kHz (right))

If the echo-free time for a particular tank with transducers optimally positioned is denoted by T, then the number of cycles available for analysis before the arrival of reflections is equal to the product fT, where f is the frequency of excitation.

If these cycles are to be used for analysis, steady-state conditions should be reached. The electroacoustic transducers used in underwater acoustics are typically resonant devices of quality-factor Q. For such devices, it takes Q cycles of the resonance frequency for the signal to reach approximately 96 % of its final steady-state value. Therefore, it will take approximately Q cycles of the resonance frequency before the initial turn-on transients have almost completely died away, even when the projector is driven off-resonance. For situations where $Q > fT$, so that steady-state is not reached within the free-time available, it is not possible to make a direct measurement of the steady-state signal.

Note that the transient behaviour observed in the signal will also depend on the Q factors of other items in the measuring system. If the receiving hydrophone has a resonance close to the frequency of measurement, this will influence the waveform shape. Similarly, if any measuring instrument (amplifier, filter, etc.) displays any resonant behaviour in the frequency range, this will also influence the transient behaviour.

By the above arguments, it can be seen that for any given size of tank, there will be a frequency (depending on the transducer Q-factor) where the accurate use of conventional measurement techniques becomes impossible [1], [2], [12], [38] and [69].

C.2.4 Bandwidth considerations

The chief disadvantage of the pulsing technique is that a pulse consists of a spectrum of frequencies whereas a continuous sinusoidal signal contains only one frequency. Undistorted transmission of a pulse through the transmitting amplifier, sound projector, hydrophone and receiving system requires a broad band and constant overall system response above and below the measuring signal frequency. Some variation from the ideal conditions will always exist [1], [70] and [71].

The transmitted pulse is generally a rectangular pulse modulating the carrier frequency, which is the measurement frequency. For measurement purposes, the bandwidth of the overall system should be two to twenty times the reciprocal of the pulse duration. A bandwidth that is approximately twice the reciprocal of the pulse duration will yield a maximum signal-to-noise ratio. The amplitude of the pulse envelope will be 2 dB above the amplitude of a square pulse transmitted by the bandwidth of twenty times the reciprocal of the pulse duration. A bandwidth that is twice the reciprocal of the pulse duration is sometimes referred to as the essential bandwidth. The application of signal averaging over repeated tone bursts can improve the signal to noise ratio considerably.

C.2.5 Electrical cross-talk

When pulsed signals are used, the electrical cross-talk may be easily identified (and eliminated) by time-windowing since it will arrive at the receiver essentially instantaneously without the time delay observed for propagation of the acoustic signal. In order to avoid interference when electrical cross-talk is present, the pulse duration should not be greater than the acoustic propagation delay, so that the two signals cannot overlap in time.

C.2.6 Pulse duration

Based on the considerations discussed above, the pulse duration τ should satisfy the following conditions [12]:

a) $\tau \le T_n$ so that the direct signal is separated from the reflected signals.

b) $\tau \ge Q / f$ so that steady state is reached.

c) $\tau \le d / c$ so that the direct signal is separated from the electrical cross-talk.

d) $\tau \ge 2 / W$ so that the direct signal is undistorted. Here W is the bandwidth of the overall measurement system including the transducers.

C.2.7 Reverberation and pulse repetition rate

With pulsed signals, it is necessary to choose a pulse repetition rate which is low enough for all reverberation in the tank to die away before transmission of the next pulse [1]. To check for reverberation, the receive signal on an oscilloscope should be observed and it should be checked that there is no signal present at the frequency of measurement during the time immediately before the pulse is transmitted.

The pulse repetition rates used in underwater acoustic calibrations in test tanks are generally in the range of a few hertz to perhaps 100 Hz with pulse durations varying from less than 0,1 ms to 10 ms depending on signal frequency and available echo-free time. A low value of pulse repetition rate may be required at low signal frequencies if reverberation is to be avoided.

C.2.8 Typical tank dimensions

Typical dimensions of tanks used for calibration of underwater acoustic transducers have minimum dimensions of 4 m or 5 m, with the lowest frequency of measurement being 1 kHz or 2 kHz (for low Q transducers). In C.2.1 to C.2.6, it can be seen that the smaller the tank, the higher will be the lower limiting frequency. In general, the smallest dimension of the tank is often the depth. In some facilities, absorbers are used on one or more internal surfaces to reduce reverberation time.

Smaller tanks of minimum dimension about 1 m are often used for calibration at high frequencies (hundreds of kilohertz) [1], [12], [38].

C.2.9 High-frequency limitations

The high frequency limit is governed by a number of factors. The minimum separation distance required permitting suitable acoustic far-field conditions to exist for a specific transducer pair increases with frequency (see equation C.2).

However, when using tone-burst signals, increasing the transducer separation distance will tend to reduce the echo-free time available for measurements before the arrival of reflected signals from the tank boundaries. A significant reduction in echo-free time will restrict the time window available for observation of the steady-state signal.

The attenuation of sound due to absorption in the water increases rapidly with frequency, reaching about 0,25 dB/m at 1 MHz for fresh water and 0,4 dB/m for seawater [46].

In general, a combination of the above factors will tend to determine the high frequency limit for calibrations. At frequencies above 0,5 MHz, consideration should be given to use of the alternative method described in IEC 60866. This alternative method is a two-transducer method, where the transmitting current response of a source transducer is first determined by the self-reciprocity method using a reflective planar target under approximately plane-wave conditions (requiring the plane-wave reciprocity parameter to be used). This auxiliary transducer is then used to calibrate the hydrophone under test by a calibrated projector method. This method is suited to transducers that produce narrow beams [1], [45], [46], see IEC 60866.

C.2.10 Low frequency limitations

The lowest frequency for calibrations is limited by several factors.

When using tone-burst signals in finite-sized test tanks, the number of cycles of steady state signal available for measurement depends on the Q factor of the transducers and the echo-free time of the test tank (which in turn depends upon tank size and transducer separation). As the frequency is lowered, the number of cycles in the available time-window is reduced until eventually the steady-state signal amplitude can no longer be determined by conventional means. This provides a lower limiting frequency on measurements made using tone-burst signals.

In addition, the sound pressure level produced by the transmitting transducer may be reduced as the frequency is lowered, eventually falling to where it is less than 20 dB above the ambient noise level thereby limiting the minimum frequency for calibrations.

NOTE For a piezoelectric transducer used well below the lowest resonance frequency, the sound pressure output at a constant current is proportional to the frequency. For an electrodynamic transducer, the sound pressure output at constant drive current decreases proportionally with the square of the frequency well below the first resonance (although the response is relatively constant between the first and second resonances).

The minimum separation distance for a given transducer size at low frequencies is given by equation (C.2).

In general, a combination of the above will tend to determine the low frequency limit for calibrations. For most large test tank facilities of minimum dimension 5 metres or greater, the practical low frequency limit for calibration of hydrophones will be of the order of 1 kHz or 2 kHz [38], [69].

C.2.11 Spherical-wave verification

The existence of a spherically-spreading acoustic field may be verified by comparison of the electrical transfer impedance magnitudes when the distance between projector and hydrophone is varied. For a spherically-spreading field, the product of the electrical transfer impedance magnitude and separation distance should be invariant with distance (see 3.10, Note 4) [12].

The degree to which this product varies with distance is an indication of the uncertainty that may be ascribed to this factor. In ideal conditions, it should be possible to obtain variation of less than ±2 %. Variation of greater than ±5 % may indicate additional problems (e.g. from boundary reflections) and should be investigated further.

C.2.12 Evidence of interference effects

NOTE 1 Where smooth periodic ripples can be observed in a plot of electrical transfer impedance (or sensitivity) against frequency, this is an indication that acoustic reflections are likely to be present leading to constructive and destructive interference effects.

If the frequency interval between successive peaks in the plot is Δf, the path difference, Δd, between the direct and reflected signals arriving at the hydrophone should be calculated by:

$$\Delta d = \frac{c}{\Delta f} \tag{C.3}$$

where c is the speed of sound [1].

NOTE 2 The path difference may be used to trace the source of reflected signals.

Care should be taken to ensure that interference from electrical cross-talk is not present during measurements. When tone-burst signals are used, the cross-talk should be easily identified (and eliminated) by time-windowing since it will arrive at the receiver essentially instantaneously without the time delay observed for the propagation of the acoustic signal. In order to avoid interference when electrical cross-talk is present, the tone-burst duration should not be greater than the acoustic propagation delay, so that the two signals cannot overlap in time.

With tone-burst signals, a tone-burst repetition rate should be chosen that is low enough for all reverberation in the tank to die away before transmission of the next pulse. To check for reverberation, the receive signal on an oscilloscope should be observed and checked to ensure that there is no signal present at the frequency of measurement during the time immediately before the tone burst is transmitted.

NOTE 3 Use of echo-reducing treatments for one or more of the walls of the tank will reduce the reverberation time and allow the use of a higher tone-burst repetition rate [1], [2].

C.3 Analysis methods for tone-burst signals

In the case where there is enough echo free-time before the arrival of the first echoes for the steady-state signal to be observed directly, a number of different methods may be employed to make an estimate of the steady-state amplitude. Typically, a time-window or gate is applied to the digitized waveform so that only a selected region of the steady-state signal is made available for analysis. Methods of measuring the amplitude of the steady-state component follow.

a) Direct measurement of the peak voltage by measuring the maximum and minimum of the digitized signal (or by a peak detector).

b) Calculating the RMS voltage (by squaring, averaging and square rooting the digitized signal). Ideally, this is done using an integer number of cycles of the sinusoidal signal.

c) Performing a fast Fourier transform (FFT) of the signal and taking the amplitude of the spectrum at the drive frequency, again using an integer number of cycles.

d) Performing a ‘narrow-band’ discrete Fourier transform (DFT) of the signal, calculating only the amplitude of the component at the drive frequency, again using an integer number of cycles.

e) Performing a least-squares fit of a sine-wave of the appropriate frequency and taking the amplitude of the fitted sine-curve.

All the above methods have strengths and weaknesses. The peak measurement of a) is simple to implement but inaccurate in the presence of any noise, distortion and residual amplitude fluctuations of the waveform envelope. The other methods need a little more processing, perhaps with dedicated software algorithms. However, methods b) to e) will provide some effective averaging of small amplitude variations if many cycles are contained within the time window. Methods c) to e) will also provide some discrimination against noise and can also provide information on phase as well as amplitude. However, errors may occur with methods b) to d) if an integer number of cycles is not used for the analysis. Also, with the FFT of method c), an error may be introduced if the spectrum does not contain a point at the exact frequency of excitation. Both methods d) and e) can still provide acceptable accuracy even when analysing only half a cycle of signal [69].

Where automatic on-board analysis is undertaken using digitizing oscilloscopes or waveform analysers, care should be taken to ensure that the on-board analysis produces accurate results [1], [2], [12], [38] and [69].

Annex D
(informative)

Assessment of uncertainty in the calibration of hydrophones

D.1 General

To be truly meaningful, the result of a calibration should be accompanied by its associated uncertainty [3].

In general, uncertainty components are grouped according to how the values are estimated:

Type A: evaluated by statistical means,
Type B: evaluated by other means.

D.2 Type A evaluation of uncertainty

This may be obtained from a statistical analysis of the repeatability of the calibrations.

Ideally, the repeated measurements should be truly independent repeats, with the hydrophones removed from the water and remounted before the calibration is repeated.

Where it is not feasible to undertake independent repeats, and where historical data exist for the repeatability of the measurements with the devices in question, values for the typical repeatability for calibration of a hydrophone may be used.

This assessment should follow a type B evaluation.

D.3 Type B evaluation of uncertainty

Type B components of uncertainty are those that are not assessed by statistical means, in other words those components that remain constant when the measurement is repeated. For example, any systematic bias in a measurement may be regarded as a Type B contribution. Similarly, the uncertainty in the calibration of a calibrated instrument provides a Type B contribution.

The sources of these components should be identified by assessing all of the influences which may introduce uncertainty into the measurement. These will be different for each measurement system and should be assessed individually. The value of each component should be estimated along with an associated probability distribution.

D.4 Reported uncertainty

The combined uncertainty should be obtained from the individual components [3]. All components should be expressed as standard uncertainties before being combined. The method used to combine the components requires the formulation of a model that relates the result of the calibration to all quantities that are measured or subject to uncertainty.

When stating the reported uncertainty, it should be expressed as expanded uncertainty. In this case, the level of confidence and the coverage factor should also be stated.

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

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

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

D.5 Common sources of uncertainty

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

Once the sources of uncertainty have been identified, each requires assessment by either a Type A or Type B evaluation. In most cases for the components listed below, a Type B evaluation is most appropriate. However, where a parameter has been estimated from repeated measurements (a possible example might be the measurement of separation distance in a reciprocity calibration), a Type A evaluation may also be required.

Sources of uncertainty specific to free-field reciprocity calibrations [1], [8], [12]:

- uncertainty of any assumptions about the acoustic field, e.g. that the field is a spherical-wave field (this may be checked by varying the separation distance between transducers and checking that the product of electrical transfer impedance and distance is invariant, see 8.6.4);
- non-reciprocal behaviour by transducers (can be evaluated by checking the equivalence of the Z_{PT} and Z_{TP} electrical transfer impedances, see 8.6.6);
- uncertainties in the measurement of the separation distance;
- uncertainties in the values for acoustic frequency (required to calculate the reciprocity parameter);
- uncertainty in the value for water density (required to calculate the reciprocity parameter).

Sources of uncertainty specific to comparison calibrations [1], [8], [12]:

- uncertainties in the calibration of the reference hydrophone (a major source of uncertainty in a comparison calibration);
- uncertainty caused by short-term instability of any auxiliary transducers used for comparison calibrations (e.g., instability of the output of a transducer used as a projector in a comparison calibration);

- uncertainty caused by potential instability of the reference hydrophone in comparison calibrations (i.e., variation in the sensitivity of the reference device since the previous absolute calibration);
- differences in environmental conditions for the comparison calibration compared with those that existed during the absolute calibration of the reference hydrophone, which would cause a change in sensitivity for the reference hydrophone (e.g. temperature, depth, mounting/rigging, etc.).

Sources of uncertainty specific to hydrophone calibration by calibrated projector method [1], [8], [12]:

- uncertainty of any assumptions about the acoustic field produced by the projector, e.g., that the field is a spherical-wave (the calibrated projector method is more sensitive to lack of free-field conditions than comparison with a calibrated hydrophone, e.g., due to interference from boundary reflections);
- uncertainties in the measurement of the separation distance;
- lack of stability in the projector electrical drive conditions, including lack of linearity if the projector is driven with a signal different than that used in its own absolute calibration;
- instability of the calibrated projector (i.e. variation in sensitivity of reference device since previous absolute calibration);
- differences in environmental conditions for the calibration compared with those that existed during the absolute calibration of the reference projector which would cause a change in sensitivity for the reference hydrophone (e.g., temperature, depth, mounting/rigging, etc.).

Sources of uncertainty common to all above methods [1], [8], [12]:

- lack of steady-state conditions, especially where bursts of single-frequency sound waves are used (the resonance frequency and Q-factors of the transducers and the echo-free time of the tank will influence this contribution);
- interference from acoustic reflections, leading to a lack of free-field conditions;
- lack of acoustic far-field conditions;
- the spatial averaging effects of the hydrophones under calibration due to their finite size and the lack of perfect plane-wave conditions;
- misalignment, particularly at high frequencies where the hydrophone response may be far from omnidirectional;
- acoustic scattering from the hydrophone mount (or vibrations picked up and conducted by the mount);
- uncertainty in measurement of the receive voltage (including uncertainty due to the measuring instrumentation (voltmeter, digitizers, etc.);
- uncertainty of the gains of any amplifiers, filters, and digitizers used;
- uncertainties in the measurement of the drive current or voltage;
- uncertainties due to the lack of linearity in the measurement system (the use of a calibrated attenuator to equalize the measured signals may significantly reduce this contribution);
- uncertainty of any electrical signal attenuators used;
- electrical noise include RF pick-up;
- uncertainty of any electrical loading corrections made to account for loading by extension cables and preamplifiers;

- bubbles or air clinging to transducers (this should be minimized by adequate wetting and soaking of transducers);
- environmental conditions, such as water temperature and depth of immersion (corrections need not be included for these if the calibration results specify the conditions and state that the calibration is only valid for the conditions stated).

Annex E
(informative)

Equivalent circuit of the excitation system for calibration with a vibrating column

E.1 Equivalent circuit

At frequencies where the length l of the column is less than a quarter of the wavelength, the vibrating column can be represented by an equivalent circuit as shown in Figure E.1. Force is represented by a voltage, mass by an inductance and compliance by capacitance.

Variation of the depth of the hydrophone is represented by displacement of the sliding contact on the coil m_w. At the lowest point on the coil $(h = 0)$, the hydrophone is at the top of the column. Upward movement of the contact slide corresponds to deeper immersion of the hydrophone.

The compliance of the hydrophone is represented by a capacitive electrical load impedance Z. At shallow depth, this load will have no influence on the equivalent output voltage pA of the circuit.

The stiffness of the hydrophone is said to be sufficiently large if its influence on pA is negligibly small at the operational depth h of the hydrophone in the column.

F_c is the generated force

m_c is the mass of the vessel

$\dot{x}$ is the velocity of the vertical motion

C is the effective wall compliance of the vessel

m_w is the mass of the liquid

Z is the mechanical impedance of the hydrophone (mainly stiffness)

A is the cross-sectional area of the liquid column

p is the sound pressure at the hydrophone

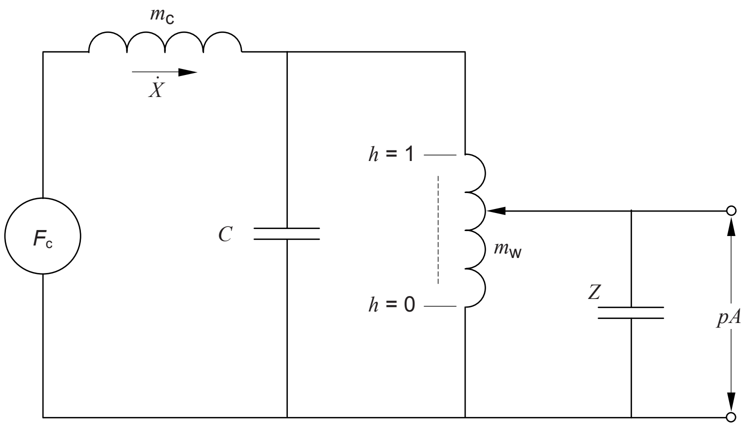

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Figure E.1 – Simplified equivalent circuit of the vibrating column

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Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-801	-[1]	International Electrotechnical Vocabulary (IEV) Chapter 801: Acoustics and electroacoustics	-	-
IEC 60500	1974	IEC standard hydrophone	-	-
IEC 60866	1987	Characteristics and calibration of hydrophones for operation in the frequency range 0,5 MHz to 15 MHz	-	-

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[1] Undated reference.

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