

INTERNATIONAL STANDARD

NORME INTERNATIONALE

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

**Acoustique sous-marine – Hydrophones – Étalonnage des hydrophones –
Partie 2: Procédures pour l'étalonnage à basse pression de fréquence**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**UNDERWATER ACOUSTICS – HYDROPHONES –
CALIBRATION OF HYDROPHONES –****Part 2: Procedures for low frequency pressure calibration**

FOREWORD

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International Standard IEC 60565-2 has been prepared by IEC technical committee 87: Ultrasonics.

This first edition of IEC 60565-2, together with IEC 60565-1, replaces the second edition of IEC 60565 published in 2006. This edition constitutes a technical revision.

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

- 1) IEC 60565 has been divided into two parts:
 - Part 1: Procedures for free-field calibration;
 - Part 2: Procedures for low frequency pressure calibration (this document).
- 2) A relative calibration method has been added to Clause 8: Calibration by piezoelectric compensation.

- 3) A relative calibration method has been added to Clause 11: Calibration by **vibrating column**.
- 4) Clause 12: Calibration by static pressure transducer, has been added.
- 5) Annex A: Equivalent circuit of the excitation system for calibration with a **vibrating column**, has been deleted.
- 6) Subclauses 9.6, 9.7 and 9.8 have been moved to form a new Annex A: Advanced acoustic coupler calibration methods.

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

FDIS	Report on voting
87/720/FDIS	87/723/RVD

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

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

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

A list of all parts in the IEC 60565 series, published under the general title *Underwater acoustics – Hydrophones – Calibration of hydrophones*, can be found on the IEC website.

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

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

INTRODUCTION

The purpose of this document is to establish the procedures for low frequency pressure calibrations of **hydrophones** in the frequency range from 0,01 Hz to several kilohertz.

To ensure the correctness of the calibrations, the **hydrophones** to be calibrated are "rigid" **hydrophones** with small size compared to the acoustic wavelength, and are not sensitive to vibration when calibrated.

Principles, procedures, and **uncertainties** of physical calibrations such as hydrostatic excitation, piezoelectric compensation, **pistonphone**, **vibrating column**, static pressure transducer, etc., and reciprocity calibrations in acoustic **couplers** are given in this document. Calibrations are carried out using one of these methods, depending on the different principles to be used, and its limitations to the sound field and the frequency range.

UNDERWATER ACOUSTICS – HYDROPHONES – CALIBRATION OF HYDROPHONES –

Part 2: Procedures for low frequency pressure calibration

1 Scope

This part of IEC 60565 specifies the methods for low frequency pressure calibration of **hydrophones** at frequencies from 0,01 Hz to several kilohertz depending on calibration method.

2 Normative references

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

IEC 60050-801, *International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics* (available at <http://www.electropedia.org/>)

IEC 60500:2017, *Underwater acoustics – Hydrophones – Properties of the hydrophone in the frequency range 1 Hz to 500 kHz*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-801, IEC 60500:2017 and the following apply.

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

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

3.1

coupler

apparatus comprising a rigid fluid-filled chamber into which transducers and **hydrophones** can be inserted whose largest dimension is small compared to the wavelength

Note 1 to entry: In this document, the term small chamber is used interchangeably with **coupler**.

[SOURCE: IEC 60565:2006 [1]¹, 3.3, modified – In the definition, "small dimensions" has been replaced by "whose largest dimension is small compared to the wavelength".]

¹ Numbers in square brackets refer to the Bibliography.

3.2

diffraction factor

ratio of the root-mean-square value of the sound pressure, averaged over the part of the **hydrophone** designed to receive an incident plane wave sound pressure from a given direction to the free-field root-mean-square sound pressure that would exist at the position of the reference centre of the **hydrophone** if the **hydrophone** was removed

Note 1 to entry: Spatial average is undertaken first and then time average.

[SOURCE: IEC 60500:2017, 3.3, modified – In the definition, "the root-mean-square sound pressure" has been replaced by "the root-mean-square value of the sound pressure," and "the position of" has been added after "that would exist at".]

3.3

electrical transfer impedance

Z_{PH}

<of a transducer pair in a coupler> quotient of the Fourier transform of the open circuit voltage $\Im(U_H(t))$ across the **hydrophone** electrical terminals, to the Fourier transform of the electrical current $\Im(I_P(t))$ through the **projector**, when **projector** and **hydrophone** are mounted in a **coupler**

$$Z_{PH} = \frac{\Im(U_H(t))}{\Im(I_P(t))} \quad (1)$$

Note 1 to entry: The **electrical transfer impedance** is a complex-valued parameter. The modulus of the **electrical transfer impedance** is expressed in ohm, Ω . The phase angle is expressed in degrees, and represents the phase difference between the **hydrophone** voltage and the **projector** current.

Note 2 to entry: Because the **electrical transfer 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, are specified.

[SOURCE: IEC 60565:2006 [1], 3.10, modified – In the term, "transducer pair" has been deleted. The domain "<of a transducer pair in a coupler>" has been added. In the definition, "complex ratio of the open circuit instantaneous voltage U_H " has been replaced by "quotient of the Fourier transform of the open circuit voltage $\Im(U_H(t))$ ", "the instantaneous current I_P " has been replaced by "Fourier transform of the electrical current $\Im(I_P(t))$ ", and "if **projector** and **hydrophone** are mounted in a free field with their principal axes in line and directed towards each other" has been replaced by "when **projector** and **hydrophone** are mounted in a **coupler**".]

3.4

hydrophone

electroacoustic transducer that produces electrical voltages in response to water borne pressure **signals**

Note 1 to entry: A **hydrophone** is designed to respond principally to underwater sound pressure.

Note 2 to entry: In general, a **hydrophone** can also produce a **signal** in response to non-acoustic pressure fluctuations (for example, those existing in a turbulent boundary layer during conditions of high water flow).

Note 3 to entry: **Hydrophone** types include reference **hydrophones** and measuring **hydrophones**. Measuring **hydrophones** are used in general measurements of sound fields, and reference **hydrophones** are principally used for calibration purposes (for example in comparison calibrations with measuring **hydrophones**).

Note 4 to entry: **Hydrophones** are principally used as listening devices, but in reciprocity calibration, a **hydrophone** is used as **reciprocal transducer**, not only acting as a **hydrophone**, but also as a **projector** (sound source).

Note 5 to entry: A **hydrophone** which is integrated with a digital acquisition system is sometimes termed a "digital **hydrophone**", but the combination is best considered as a measuring system, not a **hydrophone** alone.

Note 6 to entry: If a **hydrophone** is connected to a charge amplifier, the sensitivity of the **hydrophone** is sometimes described in terms of charge sensitivity, which is related to the voltage sensitivity of the **hydrophone** by its electrical capacitance.

[SOURCE: IEC 60500:2017, 3.17, modified – In the definition, "electrical **signals**" has been replaced by "electrical voltages".]

3.5

pistonphone

apparatus having a rigid piston which can be given a reciprocating motion of a known frequency and amplitude to establish a known sound pressure in a closed small chamber

[SOURCE: IEC 60565:2006 [1], 3.20, modified – In the definition, "so permitting the establishment of" has been replaced by "to establish", and "a closed chamber of small dimensions" by "a closed small chamber".]

3.6

pressure sensitivity

$\underline{M}_p$

<of a **hydrophone**> quotient of the Fourier transform of the **hydrophone** open-circuit voltage **signal** $\Im(U_H(t))$ to the Fourier transform of the acoustic pressure **signal** $\Im(p(t))$ averaged over the **hydrophone** active element, at a specified frequency

$$\underline{M}_p = \frac{\Im(U_H(t))}{\Im(p(t))} \quad (2)$$

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

Note 2 to entry: The term "response" is sometimes used instead of "sensitivity".

Note 3 to entry: The **hydrophone** active element is the electroacoustic element of the **hydrophone** which is sensitive to sound pressure.

[SOURCE: IEC 60500:2017, 3.23, modified – In the definition, "ratio of the root-mean-square output voltage" has been replaced by "quotient of the Fourier transform of the **hydrophone** open-circuit output voltage **signal** $\Im(U_H(t))$ ", and "root-mean-square of the sound pressure" has been replaced by "Fourier transform of the sound pressure $\Im(p(t))$ ". The description of the **hydrophone** active element has been moved to a Note to entry.]

3.7

pressure sensitivity level

L_M

twenty times the logarithm to the base 10 of the ratio of the modulus of the **pressure sensitivity** $|\underline{M}_p|$ to a reference sensitivity of M_{ref} , in decibels

$$L_M = 20 \log_{10} \frac{|\underline{M}_p|}{M_{ref}} \text{ dB} \quad (3)$$

Note 1 to entry: The value of reference sensitivity M_{ref} is 1 V/μPa.

[SOURCE: IEC 60500:2017, 3.24, modified – In the definition, "modulus of the" has been added before "**pressure sensitivity**", and "in decibels" has been added after " M_{ref} ".]

3.8**projector**

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

[SOURCE: IEC 60565:2006 [1], 3.37]

3.9**ratio of specific heats**

γ

ratio of specific heats under constant pressure and under constant volume

Note 1 to entry: For dry air and temperature 0 °C to 17 °C, $\gamma = 1,40$.

3.10**reciprocal transducer**

linear, passive, and reversible electroacoustic transducer such that the coupling coefficients are equal for transduction in either direction

[SOURCE: IEC 60565:2006 [1], 3.24, modified – In the definition, "transducer" has been replaced by "electroacoustic transducer", and "such that the coupling coefficients are equal for transduction in either direction" has been added at the end of the definition.]

3.11**signal**

specified time-varying electric current, voltage, sound pressure, sound particle displacement, or other field quantity of interest

[SOURCE: ISO 18405:2017 [2], 3.1.5.8]

3.12**transmitting response to current**

$S_{I,T}$

<of a transducer in a coupler> quotient of the Fourier transform of the acoustic pressure **signal** $\Im(p(t))$ to the Fourier transform of the electrical current **signal** $\Im(I(t))$ through a transducer T inserted into the **coupler** at a given frequency

$$S_{I,T} = \frac{\Im(p(t))}{\Im(I(t))} \quad (4)$$

Note 1 to entry: **Transmitting response to current** is expressed in units of pascal per ampere, Pa/A.

Note 2 to entry: Different with the free-field calibration, no distance term is required here.

Note 3 to entry: The acoustic pressure signal is assumed uniform in a **coupler**.

[SOURCE: IEC 60565:2006 [1], 3.36, modified – In the term, "small chamber transmitting response to current of a transducer" has been replaced by "**transmitting response to current**". The domain "<of a transducer in a coupler>" has been added. In the definition, "a small chamber" has been replaced by "a **coupler**", and "flowing through the electrical terminals of a transducer inside the chamber" by "through a transducer inserted into the **coupler**". Also, "current" has been replaced by "Fourier transform of the electrical current **signal** $\Im(U_H(t))$ ", and "ratio of the acoustical pressure (assumed uniform)" has been replaced by "quotient of the Fourier transform of the acoustic pressure signal $\Im(p(t))$ ".]

3.13

uncertainty

<of measurement> non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

[SOURCE: ISO/IEC Guide 99:2007 [3], 2.26]

3.14

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 to entry: The length of the column is sufficiently small compared with the wavelength of the sound in the water. The cross-sectional dimension of the column is small compared with its length.

[SOURCE: IEC 60565:2006 [1], 3.38]

3.15

wavenumber

k

reciprocal of the acoustic wavelength multiplied by 2π

$$k = 2\pi / \lambda \quad (5)$$

Note 1 to entry: **Wavenumber** is expressed in units of per metre, m^{-1} .

Note 2 to entry: In different branches of physics, the term **wavenumber** can be considered equal to either $2\pi/\lambda$ or $1/\lambda$, but in the technical field of acoustics, $2\pi/\lambda$ is preferred. This term given in IEC 60050-103:2009, 103-10-12 is "angular **wavenumber**".

[SOURCE: IEC 60050-726:1982 [4], 726-05-02, modified – In the definition, "the reciprocal of the waveguide wavelength or the" and "for a plane wave" have been deleted, and "acoustic" and "multiplied by 2π " have been added before and after "wavelength", respectively.]

4 Symbols

C_t	acoustic compliance of chamber
C_M	compliance of the medium
c	speed of sound in water
c_f	speed of sound in a fluid
d	depth or distance of the hydrophone
d_{jk}	piezoelectric modulus of the shell material
E	Young's modulus
f	frequency
g	acceleration due to gravity
h	displacement of the water surface in the open vessel
H_e	equivalent height
ΔH	change of the water level
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_0	hydrostatic pressure correction factor
k	wavenumber
L	length of column or coupler
L_M	pressure sensitivity level of the hydrophone
M_H	sensitivity of the hydrophone
M_p	pressure sensitivity
M_T	sensitivity of the static pressure transducer
M_M	sensitivity of the microphone
p	sound pressure
p_s	static pressure
Q	mechanical quality factor
r	radius of transducer shell
S_P	transmitting response to current of a projector in a coupler
S_T	transmitting response to current of a transducer in a coupler
U_C	compensation voltage
U_H	open-circuit voltage at hydrophone
U_M	open-circuit voltage at microphone
U_{PH}	open-circuit voltage at hydrophone with a projector as sound source
U_{PT}	open-circuit voltage at transducer with a projector as sound source
U_{TH}	open-circuit voltage at hydrophone with a transducer as sound source
U_R	open-circuit voltage at a reference hydrophone
$\underline{u}$	volume velocity
V_b	volume of the subsidiary body
V_t	total volume
ΔV	volume change
x_0	vibration amplitude
Z	contains all the terms involving transfer impedance
$\underline{Z}_{AI}$	acoustic impedance
$\underline{Z}_{PH}$	electrical transfer impedance of projector and hydrophone in a coupler
$\underline{Z}_{PT}$	electrical transfer impedance of projector and transducer in a coupler
$\underline{Z}_{TH}$	electrical transfer impedance of transducer and hydrophone in a coupler
$\underline{Z}_{TP}$	electrical transfer impedance of transducer to projector in a coupler
γ	ratio of specific heats
ρ	density of water
ρ_f	density of fluid
σ	Poisson's modulus
ω	angular frequency
ω_r	resonance angular frequency

5 Procedures for calibration

5.1 Principles

a) Absolute calibration

Calibration without a reference transducer.

b) Relative calibration

Calibration with a calibrated reference transducer.

5.2 Field limitations

The sound fields of calibrations conducted in accordance with Clauses 7 to 12 shall be restricted within a small chamber.

5.3 Schematic survey of procedures

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

- a) Calibration by hydrostatic excitation in accordance with Clause 7 is valid in the frequency range 0,01 Hz to 1 Hz.
- b) Calibration by piezoelectric compensation in accordance with Clause 8 is valid in the frequency range 1,0 Hz to 4 kHz, but with a reference transducer is usually valid in the frequency range 1,0 Hz to 2 kHz.
- c) Calibration by acoustic **coupler** reciprocity in accordance with Clause 9 is valid in the frequency range 0,1 Hz to 5 kHz.
- d) Calibration by **pistonphone** in accordance with Clause 10 with or without a reference transducer is valid in the frequency range from a few hertz to several hundred hertz.
- e) Calibration by **vibrating column** in accordance with Clause 11 with or without a reference transducer is valid in the frequency range 10 Hz to 2 kHz.
- f) Calibration by static pressure transducer in accordance with Clause 12 with a reference transducer is valid in the frequency range 0,5 Hz to 3,15 kHz.

5.4 Reporting of results

Calibration of **pressure sensitivity** or **pressure sensitivity level** is only valid on the date of calibration and for the environmental conditions which existed during the calibration. When the calibration result 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 [5] to [9].

Conditions to be reported may include:

- date of the evaluation;
- water temperature;
- depth of immersion (or applied hydrostatic pressure);
- length of soaking time and any wetting procedure adopted;
- maximum acoustic pressure experienced by the **hydrophone**;
- any assumptions made about the device under test (e.g. the position of the reference centre).

The calibration **uncertainty** shall also be reported alongside the **pressure sensitivity** or **pressure sensitivity level**, which shall be evaluated in accordance with ISO/IEC Guide 98-3 [10].

If use is made of a calibrated **hydrophone** in an environment significantly different than 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

Hydrophones shall be calibrated periodically in order to maintain a valid calibration status. For reference **hydrophones**, an annual recalibration may be appropriate. For measuring **hydrophones**, where **hydrophones** are used in the field and potentially may be subjected to abuse, calibration may be required at shorter intervals.

5.6 Temperature and pressure considerations for calibration

Properties of transducers may vary with both ambient temperature and hydrostatic pressure (depth) [6], [7].

Where the sensitivity of a transducer is required for specific conditions of water temperature and hydrostatic pressure (water depth), the transducer shall either be calibrated under the same conditions of temperature and pressure as will be applicable during use of the **hydrophone** in to measure sound fields, or corrections to transducer sensitivity and response values shall be made based on earlier calibrations or validated analytical models.

5.7 Preparation of transducers

To make sure that the transducer is wetted properly, and to ensure that there is no air film or bubbles trapped 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 [8].

6 Electrical measurements

6.1 Signal type

Typically, the excitation waveform used for the calibration is a continuous sinusoidal wave. In this case, a sufficient number of frequencies are chosen to ensure that the **hydrophone** performance is well characterized over the desired frequency range. With the development of the measurement technology, other **signals** are becoming commonplace and these include chirps and broadband noise.

6.2 Earthing

In order to avoid earth loops, the electrical terminals of the transducers shall be kept free from contact with the water. The exposed metal parts of the **hydrophone** shall have a single point earth connection with the cable screen of the **hydrophone**. All other earth contacts shall be excluded.

6.3 Measurement of hydrophone output voltage

6.3.1 General

The open-circuit voltage of the **hydrophone** shall be measured at the end of the **hydrophone** cable. The electrical terminals used for the measurement shall be specified.

When an amplifier, attenuator or filter is used and forms part of the measurement system these elements shall be calibrated.

6.3.2 Electrical loading by measuring instrument

During the measurements, the **hydrophone** shall be connected to a measuring instrument (amplifier, voltmeter, oscilloscope or digitizer) with high electrical input impedance. Typically the electrical input impedance shall be much larger than the electrical impedance of the **hydrophone** (ideally, more than 100 times larger). Where the electrical impedance of the **hydrophone** is high (for example for a small piezoelectric **hydrophone** with low electrical

capacitance), consideration shall be given to the electrical loading of the **hydrophone** caused 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 can be calculated using the procedure given in IEC 60565-1.

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

6.3.3 Electrical loading by extension cable

If an extension cable is attached to the **hydrophone**, this cable will electrically load the **hydrophone** and a correction shall be applied to obtain the open-circuit voltage of the **hydrophone**.

NOTE 1 The corrections at low frequencies are calculated using the procedure given in IEC 60565-1. For high frequency, the corrections can make use of the method developed by Hayman, et al., see [11].

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

6.3.4 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. Acoustic interference levels that are at least 30 dB lower than the **signal** levels, or at least 40 dB lower than the **signal** levels for continuous wave **signal**, are unlikely to compromise measurement **uncertainty**.

6.3.5 Integral pre-amplifier

When a **hydrophone** has an integral pre-amplifier, the sensitivity is expressed as end-of-cable sensitivity including the performance of the pre-amplifier.

NOTE When a **hydrophone** has an integral pre-amplifier that is matched to the electrical impedance of the measurement system, a correction for electrical loading by extension cables or measuring instruments is unnecessary.

6.4 Measurement of projector current

The current through the **projector** shall be determined either by a calibrated current clamp, 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 series with the **projector**.

7 Calibration by hydrostatic excitation

7.1 General

This method of **hydrophone** calibration without a reference transducer applies to the frequency range 0,01 Hz to 1 Hz by harmonically changing hydrostatic pressure. It is an absolute calibration of **hydrophones** and is carried out in a small chamber [12] to [14]. For the implementation described here, this calibration method provides a value of the modulus of the **hydrophone** sensitivity only.

7.2 Principle

7.2.1 Determination of the alternating pressure

Connect a closed small chamber to an open vessel such that the water level in the vessel is always higher than the chamber. The open vessel is subject to harmonic movement in the

vertical direction (see Figure 1). The displacement of the water surface in the open vessel h can be expressed as:

$$h = h_0 \cos \omega t \quad (6)$$

where

h_0 is the amplitude of the displacement of the water surface;
 ω is the angular frequency of vibration.

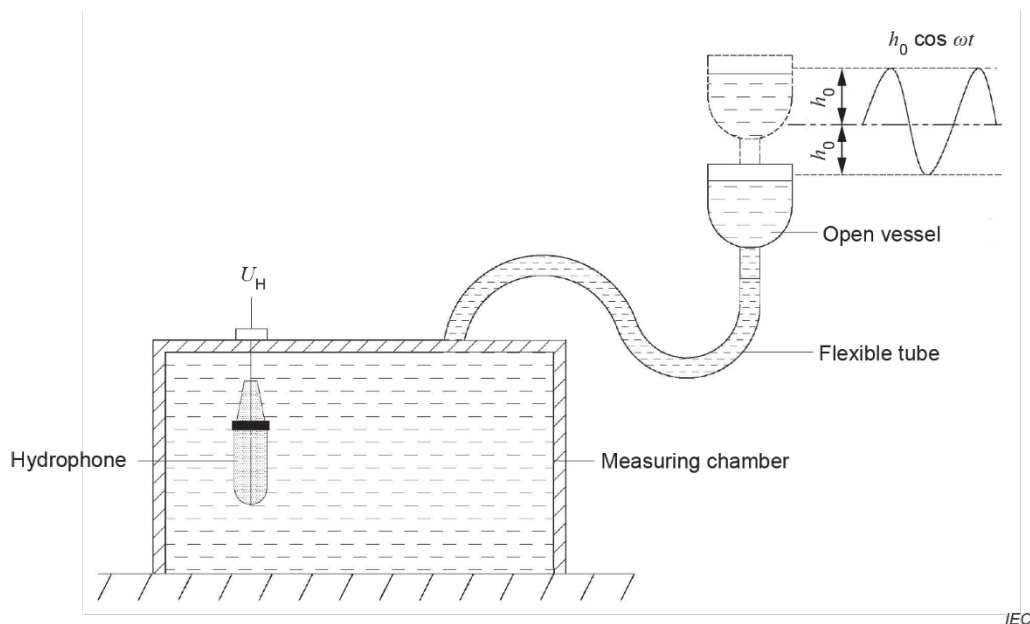


Figure 1 – Diagram of calibration by hydrostatic excitation

The variation of the water level in the open vessel produces an alternating pressure p in the closed chamber:

$$p = p_0 \cos \omega t \quad (7)$$

where

p_0 is the amplitude of the alternating sinusoidal pressure.

NOTE In practice, there is no visible time delay which can be monitored when the open vessel is harmonically moving in the vertical direction.

The alternating 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:

$$p_0 = \rho g h_0 \quad (8)$$

where

ρ is the density of water;
 g is the acceleration due to gravity.

At high frequencies, the alternating pressure p is influenced by both the Helmholtz resonance of the system and the inertia of the water in the open vessel and the connecting tube.

resonance of the system will increase the alternating pressure, and the inertia of the water will reduce the alternating hydrostatic pressure. As a result, the amplitude of the alternating pressure in the measuring chamber is then determined using the following equation:

$$p_0 = \rho g h_0 K_0 \left(1 - \frac{\omega^2}{g} H_e \right) \quad (9)$$

where

K_0 is the pressure correction factor which increases the alternating pressure;
 H_e is the equivalent height influenced by the inertia of water in the vessel and tube.

7.2.2 Determination of the correction factor

At very low frequencies, the Helmholtz resonance of the system is described using one-dimensional lumped parameters. The value of the correction factor K_0 shall be calculated by the expression:

$$K_0 = \frac{1}{\left(1 - \frac{\omega^2}{\omega_r^2} \right) \sqrt{1 + \left(\frac{\omega}{Q\omega_r} \right)^2} \left(1 - \frac{\omega^2}{\omega_r^2} \right)^2} \quad (10)$$

where

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

Under conditions of $\omega_r \gg \omega$ and $Q > 2$, Equation (10) can be expressed with sufficient accuracy as:

$$K_0 \approx 1 + \left(\frac{\omega}{\omega_r} \right)^2 \quad (11)$$

The resonance angular frequency ω_r shall be measured and verified after the calibration system has been constructed. For this purpose, a piezoelectric **projector** is mounted at the bottom of the measuring chamber and driven by a sweep **signal** generator in the frequency range which contains the resonance frequency. A **hydrophone** with constant sensitivity over this frequency range is installed in the chamber and its open-circuit output voltage is measured. The lowest resonance angular frequency of both the **projector** and the **hydrophone** shall be much greater than ω_r . The angular resonance frequency of the system can be determined according to the frequency response of the output voltage of the **hydrophone**.

7.2.3 Determination of the equivalent height

7.2.3.1 General

The equivalent height H_e shall be determined in accordance with 7.2.3.2, 7.2.3.3 or 7.2.3.4 [15].

7.2.3.2 Alternating pressure null method

The alternating pressure in the measuring chamber can be adjusted to zero in two different ways.

- a) By adding or removing water in the open vessel to change the water level, the alternating pressure p in the measuring chamber can be adjusted to zero at a specified angular frequency ω_0 . From Equation (9) the equivalent height is now given by:

$$H_e + \Delta H = \frac{g}{\omega_0^2} \quad (12)$$

where

ΔH is the change of water level.

The water level is changed again by an amount $-\Delta H$ to restore the equivalent height to its original value. The equivalent height is then given by:

$$H_e = \frac{g}{\omega_0^2} - \Delta H \quad (13)$$

- b) While keeping the water level in the open vessel at a suitable height, the alternating pressure in the measuring chamber can be adjusted to zero by varying the frequency. The equivalent height is now equal to g/ω_0^2 , where ω_0 is the angular frequency at which the alternating 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 angular frequency limit of the calibration range. If the water level is changed by an amount $-\Delta H$ to restore the alternating pressure to a suitable value, the equivalent height at this point can be obtained using Equation (13).

7.2.3.3 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 an angular frequency ω , measure the open-circuit voltage amplitude U_{H1} 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 amplitude of the **hydrophone**, U_{H2} . With these two measurements, the equivalent height shall then be determined according to Equation (14):

$$H_e = \frac{g}{\omega^2} + \frac{U_{H1}\Delta H}{U_{H2} - U_{H1}} \quad (14)$$

The two voltage amplitude U_{H1} and U_{H2} should be measured in a common manner, e.g. both as RMS or both as peak values.

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

7.2.3.4 Two frequencies method

With the open vessel vibrating first at the angular frequency ω_1 and then at the angular 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_{H1} and U_{H2} of the **hydrophone** in the closed chamber. The following assumptions shall be made.

- The sensitivity of the **hydrophone** is almost the same at two close angular frequencies, which are much lower than the resonance angular frequency of the **hydrophone**.
- The **hydrophone** will suffer nearly the same influence of the Helmholtz resonance of the system at two closely spaced angular frequencies. In this case, the equivalent height is given by the expression:

$$H_e = g \frac{U_{H2} - U_{H1}}{U_{H2}\omega_1^2 - U_{H1}\omega_2^2} \quad (15)$$

NOTE The alternating 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 needs to operate 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.

7.2.4 Calculation of the pressure sensitivity of hydrophone

The modulus of the **pressure sensitivity** $|M_p|$ of a **hydrophone** placed into the measuring chamber (see Figure 1) in terms of the amplitude of the open-circuit voltage U_{H0} shall be calculated by:

$$|M_p| = \frac{U_{H0}}{p_0} \quad (16)$$

7.3 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 **signal**-to-noise ratio of measurement. However, to keep the system vibrating smoothly near the upper frequency limit, the vibrating displacement h_0 shall not be too big. In practice, a suitable displacement of vibration is 20 mm.
- b) In practice, the following condition of the Helmholtz resonance angular frequency of the system, $\omega_r \geq 20\omega$, consisting of the vibrating of measuring chamber, soft pipe and open vessel, shall be satisfied, to ensure that

$$K_0 \approx 1 \quad (17)$$

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

$$\omega^2 h_0 \ll g \quad (18)$$

NOTE Commercial electrodynamic shaker usually not works at such low frequency and a special vibration system needs to be designed and manufactured. One method is to change rotary motion into vertically harmonic vibration, and stepper motor is usually used for control the rotational velocity accurately. 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, a good solution is to use dual stepper motors driven in a differential mode.

7.4 Alternative method for hydrostatic excitation

The hydrostatic pressure can also be varied by changing the depth of the **hydrophone** with simple harmonic motion. In this case, the alternating pressure amplitude p_0 is given by Equation (8) and the modulus of the **pressure sensitivity** $|M_p|$ is calculated from Equation (16).

This method of hydrostatic excitation introduces additional **uncertainty** sources including:

- hydrodynamic flow around the **hydrophone**. This is dependent upon the shape of the **hydrophone**.
- inertial effects of the medium. These 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.

- inertial effects within the **hydrophone**. These can also be minimized by orientation although the optimum orientation might not be the same one that minimizes the inertial effects of the medium.
- unwanted turbulence dynamic pressure. This can be minimized by making all fixtures as streamlined as possible. There is also the possibility that the harmonic motion of the **hydrophone** can excite a resonance within the water inside the calibration chamber.

7.5 Uncertainty

It is expected that the overall expanded **uncertainty** of the calibration at frequencies from 0,05 Hz to 0,5 Hz can be less than 0,3 dB (95 % confidence level) with careful practice. However, the **uncertainty** will increase to 0,5 dB (95 % confidence level) at the higher and lower extremes of the frequency range. For the alternative method, it is expected that the overall expanded **uncertainty** of the calibration can be less than 0,7 dB (95 % confidence level) with careful practice [12], [16].

8 Calibration by piezoelectric compensation

8.1 General

This method of **hydrophone** calibration applies to the frequency range 1,0 Hz to 4 kHz by piezoelectric compensation, but the method of **hydrophone** calibration with a reference transducer applies to the frequency range 1,0 Hz to 2 kHz. It is carried out in a small closed water-filled chamber, with its wavelength sufficiently larger than the largest dimension of the chamber [17] to [20]. For the implementation described here, this calibration method provides a value of the modulus of the **hydrophone** sensitivity only.

8.2 Principle

8.2.1 Determination of the sound pressure

Place the **hydrophone** inside a closed water-filled tank, equipped with a **projector** and a piezoelectric null transducer, and close to the geometric centre of the null transducer (see Figure 2). 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. The small annular gap between the shells is filled with an elastic coupling substance. Measure the value of the alternating pressure produced by the **projector** in the tank using the null transducer.

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 **projector** until the output voltage at the outer shell is zero. Use the same **signal** generator feeding the **projector** and the driving shell.

For frequencies higher than 1 kHz, the calibration chamber shall be in accordance with 8.3.2.

When the simultaneous influences of the **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 is then equal to:

$$p = K(d_{jk}, E, r) U_c \quad (19)$$

where

$K(d_{jk}, E, r)$ 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 .

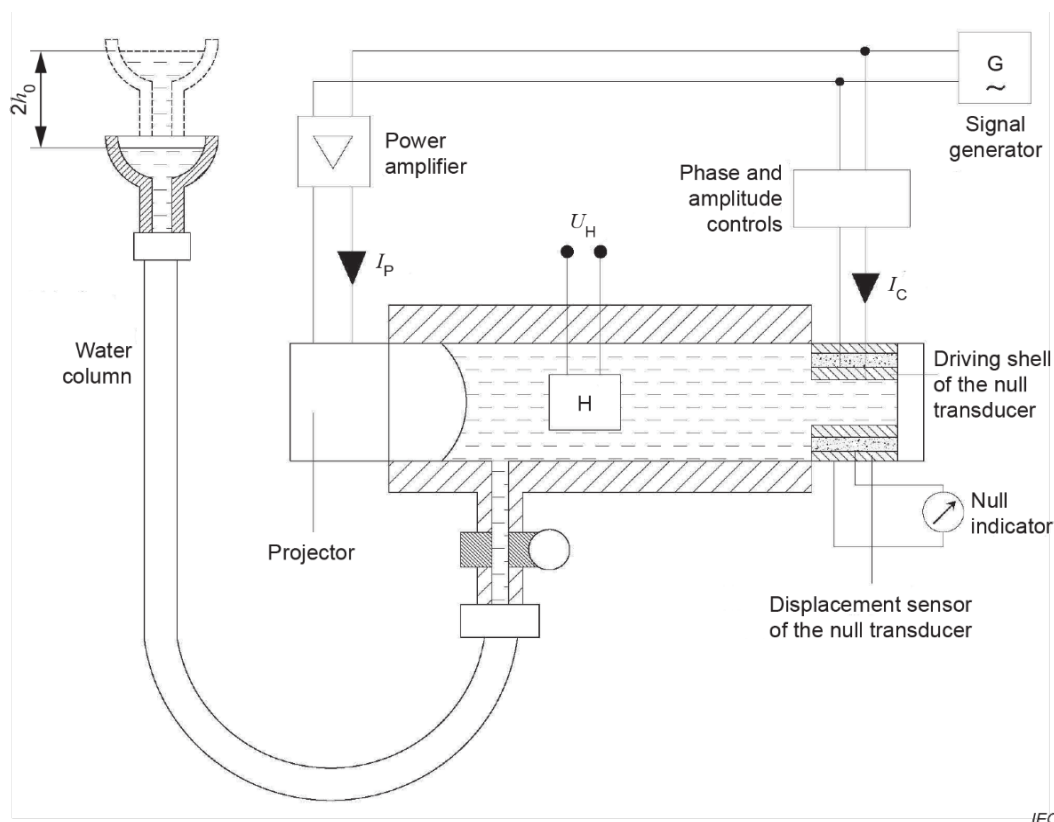


Figure 2 – Schematic drawing of calibration by piezoelectric compensation

8.2.2 Determination of the characteristic constant

The characteristic constant $K(d_{jk}, E, r)$ is generally independent of the frequency. It is 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 U_{c0} at the null transducer (see Figure 2). 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.

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 shall be low enough (0,3 Hz) to allow the inertial forces arising in the vibrating liquid to be neglected.

The amplitude of the compensation voltage U_{c0} and its phase are adjusted until the displacement of the null transducer is zero.

Then:

$$K(d_{jk}, E, r) = \frac{p_0}{U_{c0}} = \frac{\rho g h_0}{U_{c0}} \quad (20)$$

8.2.3 Calculation of the pressure sensitivity of hydrophone

The modulus of the **pressure sensitivity** $|M_{p,H}|$ of the **hydrophone** H in terms of the open-circuit voltage U_H is equal to:

$$|M_{p,H}| = \frac{U_H U_{c0}}{\rho g h_0 U_c} \quad (21)$$

8.3 Design of the calibration chamber

8.3.1 General

Depending on the frequency range, two types of chamber are used in the piezoelectric compensation method, one for low frequencies and another for high frequencies.

8.3.2 Low frequency chamber

The low frequency chamber shall be constructed from a section of pipe fitted with lids on both ends. A **projector** and null transducer shall be mounted on the lids (see Figure 2). The geometric centres of the transducers shall be located in the same horizontal plane.

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

The following precautions shall be taken.

- The tank shall be constructed in such a way that entrapped air can readily be removed.
- The acoustic compliance of the tank walls shall be less than the compliance of the water volume.
- Tongue-and-groove or metal gasketing is preferable to more compliant seals.
- The tank shall be designed and the **projector** mounted in such a way that excitation of flexural modes of vibration of the tank walls is minimized.
- All necessary measures are 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.

8.3.3 High frequency chamber

The high frequency chamber shall be as shown in Figure 3. 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 **projector**, a piezoelectric ceramic **projector** mounted in the bottom of the chamber. This **projector** shall produce a sufficient 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 8.3.2 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.

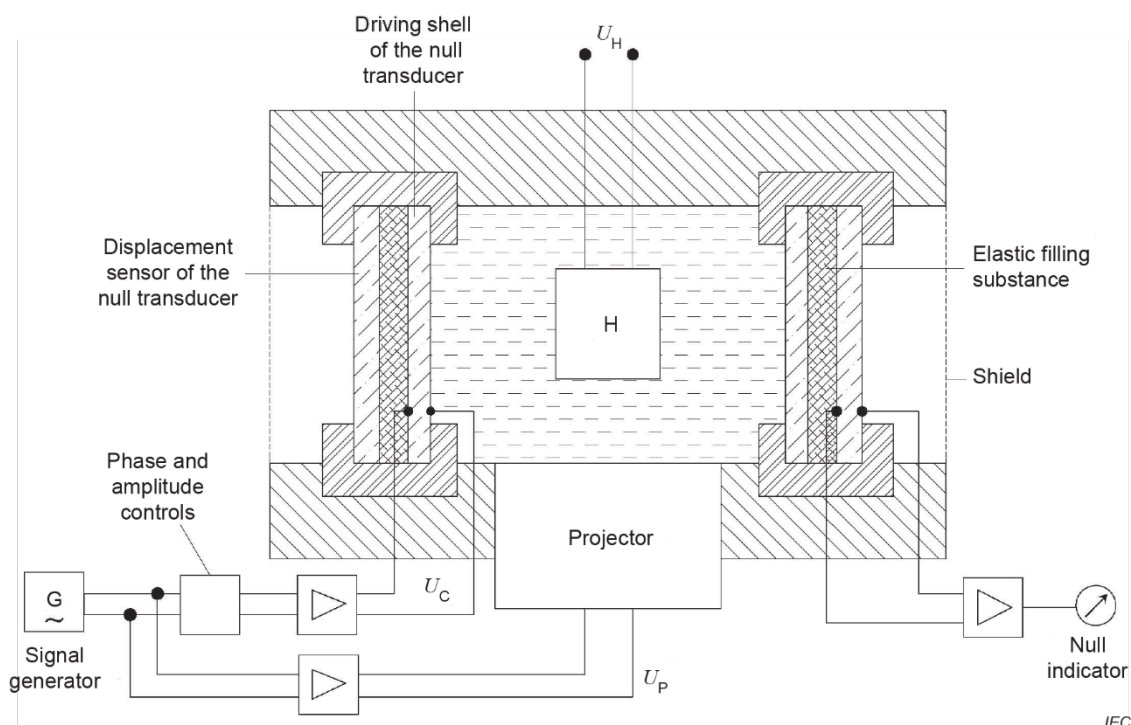


Figure 3 – Diagram of the chamber for high frequency

8.4 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 can 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 4 kHz can be covered by this method.

NOTE 2 If the **hydrophone** is symmetrical, it can 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 [17].

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 omni-directional **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.

8.5 Relative calibration method

In this method, a **projector** is used to produce the sound pressure field in the closed chamber, and a calibrated transducer and the unknown **hydrophone** are simultaneously or alternatively inserted into the chamber, and the applied calibration frequency range is 1 Hz to 2 kHz.

The modulus of the **pressure sensitivity** $\left| \underline{M}_{p,H} \right|$ of the hydrophone to be calibrated shall be calculated from Equation (22):

$$\left| \underline{M}_{p,H} \right| = \frac{U_H}{U_0} \left| \underline{M}_{p,R} \right| \quad (22)$$

where

U_H is the open-circuit voltage at the **hydrophone** to be calibrated;

U_R is the open-circuit voltage at the reference **hydrophone**;

$\left| \underline{M}_{p,R} \right|$ is the modulus of the **pressure sensitivity** of the reference **hydrophone**.

Limitations are in accordance with 8.3. The measurement procedure is convenient and simple. The method is widespread and can be used for calibration in the frequency range from 1 Hz to 2 kHz. If the calibrated transducer and the unknown **hydrophone** are alternatively inserted into the chamber, they shall be identical, otherwise additional sources of **uncertainty** arise because of different conditions in the chamber (change of flexibility, ingress of air bubbles, etc. when the **hydrophones** are reinstalled).

8.6 Uncertainty

If the conditions given in 8.3 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 0,5 dB (95 % confidence levels) with careful practice. 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). For the relative calibration method, it is expected that the overall expanded **uncertainty** can be less than 1,2 dB (95 % confidence levels).

9 Calibration by acoustic coupler reciprocity

9.1 General

This method of **hydrophone** calibration without a reference transducer applies to the frequency range 0,1 Hz to 5 kHz by acoustic **coupler** reciprocity. It is an absolute calibration of **hydrophones** and is carried out in a **coupler** using the reciprocity principle [21] to [23]. This method is suitable for determination of the sensitivities of **hydrophones** depending on the temperature and static pressure. For the implementation described here, this calibration method provides a value of the modulus of the **hydrophone** sensitivity only.

9.2 Principle

9.2.1 Theory of acoustic coupler reciprocity

The arrangement of transducers in a **coupler** for reciprocity calibration shall be in accordance with Figure 4. A **reciprocal transducer** T, a linear electro-acoustic sound source P and a **hydrophone** H are mounted in a fluid-filled **coupler**. Measure the modulus of the **electrical transfer impedance** at a number of frequencies throughout the frequency range of interest, when using the **reciprocal transducer** as a **projector** and the **hydrophone** as a receiver, or using the sound source as a **projector** and alternately the **reciprocal transducer** and the **hydrophone** as receivers. From the three transfer impedances measured at each frequency, the **pressure sensitivity** M_p of the **hydrophone** can be calculated.

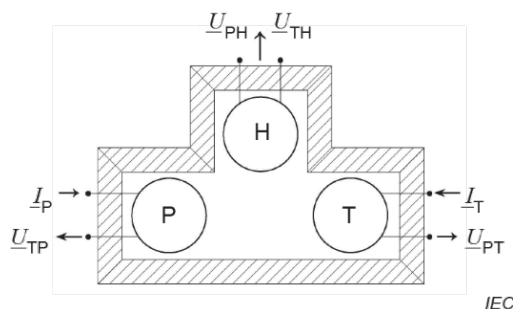


Figure 4 – Reciprocity coupler with three transducers: a projector P, a reciprocal transducer T, and a hydrophone H to be calibrated

9.2.2 Procedures for the reciprocity calibration

The derivation of the equations for the sensitivity of the three devices is given in Clause A.1.

The modulus of the **pressure sensitivity** $|M_{p,H}|$ of the **hydrophone** H is calculated from:

$$|M_{p,H}|^2 = \omega C_t \frac{|Z_{PH}| |Z_{TH}|}{|Z_{PT}|} \quad (23)$$

where C_t is the total acoustic compliance of the **coupler** (9.2.4).

The moduli of the **pressure sensitivity** $|M_{p,T}|$ and the **transmitting response to current** $|S_{I,T}|$ of the transducer T are calculated from Equations (24) and (25):

$$|M_{p,T}|^2 = \omega C_t \frac{|Z_{PT}| |Z_{TH}|}{|Z_{PH}|} \quad (24)$$

$$|S_{I,T}|^2 = \frac{1}{\omega C_t} \frac{|Z_{PT}| |Z_{TH}|}{|Z_{PH}|} \quad (25)$$

Similarly, the modulus of the **transmitting response to current** $|S_{I,P}|$ of the **projector** P is given by:

$$|S_{I,P}|^2 = \frac{1}{\omega C_t} \frac{|Z_{PH}| |Z_{PT}|}{|Z_{TH}|} \quad (26)$$

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** modulus $|Z_{TP}|$ can also be determined. Now it can be shown by the principle of reciprocity that $|Z_{TP}|$ is equal to $|Z_{PT}|$. Thus, $|Z_{PT}|$ 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 angular frequency indicates lack of reciprocity or linearity, or can be due to a measuring error. The **uncertainty** of the mean value is in general 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** is in general 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.

9.2.3 Calculation of transfer impedance

The **electrical transfer impedance** between a transmitting device (**projector** or **reciprocal transducer**) and a receiving device (**hydrophone** or **reciprocal transducer**) is calculated from the measured values of the current in the transmitting device and voltage in the receiving device (3.3).

For highest accuracy, the current shall be measured through the same measuring channel as the receive voltage (the measuring channel in general consists 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 can 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.

9.2.4 Determination of 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 acoustic compliance is given by:

$$C_t = \frac{V_f}{\rho_f c_f^2} \quad (27)$$

where

ρ_f is the density of the fluid;

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 acoustic 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. [24].

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.

9.3 Limitation of acoustic coupler reciprocity

9.3.1 Frequency limit

9.3.1.1 High-frequency limit

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

NOTE In some instances, it is possible to calculate the acoustic 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.

9.3.1.2 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 will 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.

9.3.2 Hydrophone limit

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

Hydrophones that can be calibrated in the reciprocity **coupler** should 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** should be known. They should 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**, process can be extended by using the techniques described in Annex A.

9.4 Measurement

9.4.1 General

Measurement shall be carried out in accordance with 6.3, 6.4, and as follows.

9.4.2 Evidence of interference effects

Interference from electrical cross-talk shall not be present during measurements.

9.4.3 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** moduli 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 transfer impedances of a few per cent.

NOTE 2 Disagreement of greater than $\pm 5\%$ 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 can reveal which of the transducers is non-reciprocal. In a reciprocity calibration, non-**reciprocal transducers** can only be used as a **projector** or **hydrophone** (as appropriate).

Large discrepancies between $|Z_{PT}|$ and $|Z_{TP}|$ can occur if one (or both) transducers are driven too hard, resulting in non-linear behaviour. In this case, reducing the amplitude of the drive **signal** to the transducers will improve the agreement. 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) can result in non-reciprocal behaviour and degradation in the accuracy of the calibration.

NOTE 4 Calibration of a **hydrophone** over a broad frequency range can 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 can be nonlinear to the same extent and still appear reciprocal. Therefore, the reciprocity verification is best performed using transducers of different construction before either can be assumed to be reciprocal.

9.4.4 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 moduli 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 modulus of the transfer impedance shall remain constant within $\pm 5\%$.

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

9.5 Uncertainty

If the reciprocity, linearity, and high-frequency limit conditions are satisfied as specified in 9.3.1.1, 9.4.3, and 9.4.4, then, the overall expanded **uncertainty** (95 % confidence levels) of the calibration can be less than 0,5 dB with careful practice.

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 maximum 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, see Annex A.

NOTE 3 If a **hydrophone** has a pre-amplifier, 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 open-circuit 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.

10 Calibration by pistonphone

10.1 General

This method of **hydrophone** calibration with or without a reference transducer applies to the frequencies from a few hertz to several hundred hertz by **pistonphone** in a closed chamber. This chamber can be filled with air or partly filled with water [12], [25] to [27]. For the implementation described here, this calibration method provides a value of the modulus of the **hydrophone** sensitivity only.

10.2 Principle

10.2.1 Determination of the sound pressure

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 can be driven by an electric motor or moving-coil transducer. The acoustic pressure p in the chamber for a specific circular frequency ω shall be calculated from knowledge of the acoustic impedance, $|Z_{AI}|$, and the volume velocity, $|u|$:

$$p(\omega) = |u| |Z_{AI}| \quad (28)$$

NOTE The sinusoidally varying volume velocity can be written in terms of the derivative of the volume change ΔV .

Calculate the acoustic pressure p in the chamber using Equation (29):

$$p(\omega) = |j\omega\Delta V| \frac{1}{|j\omega C_M|} = \frac{\Delta V}{C_M} \quad (29)$$

where

C_M is the compliance of the medium;

ΔV is the volume change.

Clearly the sound pressure generated is independent of frequency and therefore shall be calculated from knowledge of ΔV and C_M . The change in volume can be determined from the area of the piston and the piston displacement, with the displacement measured using an accelerometer (with the output integrated with respect to time), or using an optical interferometer [26], [27].

10.2.2 Determination of the compliance of the medium

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 1 The compliance can be taken to be the compliance of only the medium since the compliance of the chamber boundaries and **hydrophone** are generally much smaller than the medium.

The compliance shall be calculated from the gas laws:

$$C_M = \frac{V_t}{\gamma p_s} \quad (30)$$

where

V_t is the total volume;

p_s is the static pressure;

γ is the **ratio of specific heats** for the gas.

NOTE 2 If necessary at very low frequencies, corrections can to be made to C_M , for example, to account for the heat conduction of the chamber walls.

10.2.3 Calculation of the pressure sensitivity

For a **pistonphone** used to obtain an absolute calibration, the modulus of the **pressure sensitivity** $|M_p|$ of the **hydrophone** shall be calculated from the **hydrophone** voltage U_H :

$$|M_p| = \frac{U_H V_t}{\Delta V \gamma p_s} \quad (31)$$

In the calculation, the metrics for the sinusoidal signals for the **hydrophone** voltage and volume velocity must be the same (e.g. both peak amplitude, or both RMS).

10.3 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 can be made for these wave modes, but the **uncertainty** of 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** will then 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** will 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. These effects are in general negligible for frequencies greater than 5 Hz, but corrections can be made to enable the method to be used at frequencies below 1 Hz [26], [27].

NOTE3 Departure from purely adiabatic conditions can 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.

10.4 Relative calibration

10.4.1 Comparison with a 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 change and compliance do not need to be calculated.

The reference device used shall be a calibrated microphone. The modulus of the **pressure sensitivity** $|\underline{M}_p|$ of the **hydrophone** shall be calculated from:

$$|\underline{M}_p| = \frac{U_H}{U_M} |\underline{M}_M| \quad (32)$$

where

U_M is the receive voltage of the microphone;

M_M is the 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 can be regarded as constant throughout the chamber at low frequencies.

10.4.2 Comparison using air–water pistonphone

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 [12], [28].

NOTE 1 Figure 5 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 wavelength) in the water medium, the frequency at which the pressure is no longer uniform is increased. If the chamber design is kept simple and symmetric, a uniform acoustic pressure will be achieved over the largest frequency range.

NOTE 3 A completely water-filled **pistonphone** has also been used [13]. However, unlike the case of an air medium, here the compliance of the boundaries will no longer be small compared with that of the water (the **hydrophone** boot, cable and boundary walls can all contribute), requiring the compliance to be measured during each calibration.

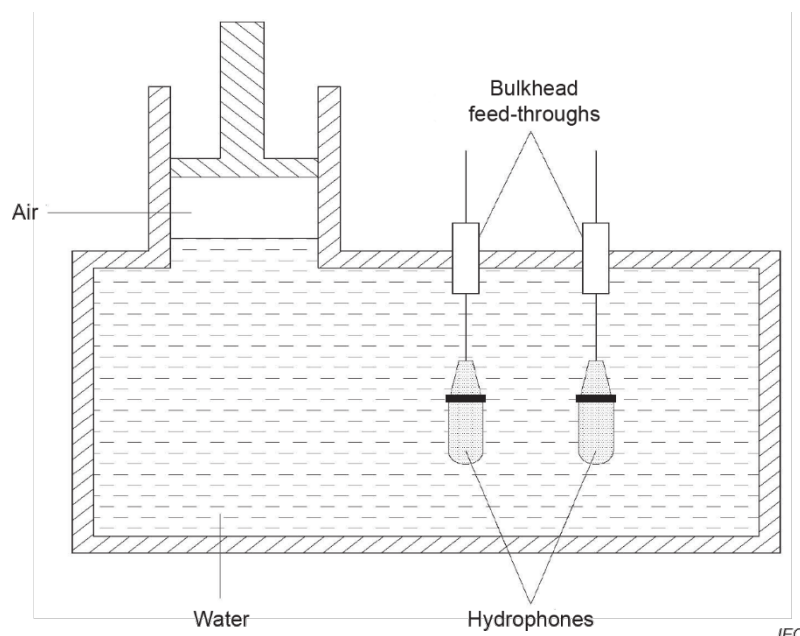


Figure 5 – Comparison calibration using pistonphone with calibrated hydrophone

10.5 Uncertainty

The overall **uncertainty** shall be evaluated and stated with the **hydrophone** sensitivity. If the conditions specified in 10.2 and 10.3 are satisfied, the overall expanded **uncertainty** (95 % confidence levels) of the calibration shall be less than 0,5 dB. 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).

11 Calibration by vibrating column

11.1 General

This method of **hydrophone** calibration with or without a reference **hydrophone** applies to the frequency range 10 Hz to 2 kHz by **vibrating column**. It is carried out in an open chamber, with its wavelength larger than the length of the column, allowing a **hydrophone** to be calibrated in a simple way [12], [29]. For the implementation described here, this calibration method provides a value of the modulus of the **hydrophone** sensitivity only.

11.2 Principle

11.2.1 General

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