

Specification for

The calibration of hydrophones

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National foreword

This British Standard has been prepared under the direction of the Electronic Equipment Standards Committee. It is identical with IEC Publication 565:1977 “*Calibration of hydrophones*” and IEC 565A:1980 (the first Supplement to this publication), published by the International Electrotechnical Commission (IEC).

Terminology and conventions. The text of the International Standard has been approved as suitable for publication, without deviation, as a British Standard. Some terminology and certain conventions are not identical with those used in British Standards; attention is especially drawn to the following.

Wherever the words “Recommendation” or “Publication” appear, referring to this standard, they should be interpreted as “British Standard”.

Scope. It is customary for a British Standard to contain only one scope clause. Attention is drawn to the fact that, in this standard, scope information is given in clauses 1, 7.1, 8.1, 9.1, 10.1 and 11.1.

Cross-references

International Standard	Corresponding British Standard
IEC 27	BS 1991 <i>Letter symbols, signs and abbreviations</i> Part 6:1975 <i>Electrical science and engineering</i> (Related)
IEC 50(08):1960:Chapter 8	BS 661:1969 <i>Glossary of acoustical terms</i> (Related)
IEC 500:1974	BS 5653:1978 <i>Specification for hydrophones for calibration purposes</i> (Identical)
ISO 31	BS 1991 <i>Letter symbols, signs and abbreviations</i> Part 1:1976 <i>General</i> (Related)
ISO 266:1975	BS 3593:1963 <i>Recommendation on preferred frequencies for acoustical measurements</i> (Technically equivalent)

At present there are no corresponding British Standards for the remainder of the International Standards referred to.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 42, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

List of symbols

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_{mt}	Mechanical compliance of chamber
C_t	Acoustical compliance of chamber
C_w	Acoustical compliance of water volume in chamber
c	Speed of sound in water
D	Mean diameter of cylindrical shell
D_i	Directivity index
d	Distance between projector and hydrophone
d_{31}	Piezoelectric modulus
E	Young's modulus
f	Frequency
g	Gravitational constant
H	Dimensional correction factor in equation (A9)
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	Attenuation of calibrated attenuator
L	Length of tank or chamber
l	Conductor length of transducer coil
M_f	Free field sensitivity
M_H	Free field sensitivity of hydrophone
M_T	Free field sensitivity of transducer
M_p	Pressure sensitivity
M_o	Sensitivity constants (Appendix B)
m	Mass of water inside chamber
P	Sound pressure
R	Resistance
R_c	Current measuring resistance
R_i	Insert voltage resistance
R_θ	Directivity factor
r	Radius of transducer shell
dS	Differential area on a sphere
S	Transmitting response to current
S_p	Transmitting response to current of a projector
S_T	Transmitting response to current of a transducer

t	Thickness of cylindrical shell
U	Voltage
U_c	Compensating voltage at null projector
U_H	Open circuit voltage at hydrophone
U_P	Transmitting voltage at projector
U_R	Voltage across resistor
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
x	Displacement of null transducer, vibration amplitude
Y	Transmission factor of attenuator
Z	Impedance
Z_{RC}	Impedance of R-C circuit
Z_{PH}	Transfer impedance of projector and hydrophone
Z_{TH}	Transfer impedance of transducer and hydrophone
Z_{PT}	Transfer impedance of transducer and projector
γ	Gain of amplifier
θ	Vertical angle
λ	Wavelength of sound in water
ρ	Density of water
σ	Poisson's modulus
φ	Azimuth angle
κ	Ratio of specific heats

1 Scope

This standard specifies methods for the measurement of the sensitivity of hydrophones, particularly in the frequency range from 1 Hz to 1 MHz, and establishes rules for the presentation of the calibration data.

2 Purpose

To establish procedures for the calibration of hydrophones.

3 Definitions

Letter symbols, terminology and scales and sizes of graphic data representation shall be in accordance with IEC Publications 27, Letter Symbols to be Used in Electrical Technology; 50(08), International Electrotechnical Vocabulary (I.E.V.), Chapter 08: Electro-acoustics; 263, Scales and Sizes for Plotting Frequency Characteristics and Polar Diagrams, and ISO Standard 31.

3.1

free field

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

3.2

far field

the 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.

3.3

acoustic centre

the point on or near a transducer from which the spherically divergent sound waves emitted by that transducer and observable at remote points appear to diverge

3.4

hydrophone

a transducer that produces electric signals in response to waterborne 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.

3.5

underwater sound projector

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

NOTE For the purpose of this standard, an underwater sound projector is called a “projector”.

3.6

reversible transducer

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

3.7

reciprocal transducer

a linear, passive, reversible transducer

3.8

open-circuit voltage at hydrophone

the voltage appearing at the electrical terminals of a hydrophone when no current passes through the terminals

Symbol: U_H .

Unit: volt, V.

NOTE 1 Throughout this standard, all voltages, currents and sound pressures are root mean square quantities, unless otherwise stated.

NOTE 2 If any electrical load, such as a cable, a transformer or an amplifier, is connected to the hydrophone, the open circuit voltage is defined as the voltage appearing at the electrical terminals of the hydrophone as measured by the “insertion voltage technique” (see Sub-clause 6.3.2).

3.9 Free-field sensitivity of a hydrophone

The ratio of the open circuit voltage of the hydrophone to the sound pressure in the undisturbed free field in the position of the acoustic centre of the hydrophone if the hydrophone were removed.

Symbol: M_f .

Unit: volt per pascal, V/Pa.

NOTE 1 The pressure may be either sinusoidal or narrow band filtered noise, the geometric mean value between the frequency band limits being considered as the given frequency.

NOTE 2 The frequency as well as the terminals to which the sensitivity refers shall be specified.

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

3.9.1

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 M_{ref} is equal to 1 V/μPa.

Unit: decibel, dB.

NOTE 2 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.

3.10 Pressure sensitivity of a hydrophone

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

See Notes 2 and 3 of Sub-clause 3.9.

Symbol: M_p .

Unit: volt per pascal, V/Pa.

3.10.1 pressure sensitivity level

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

Unit: decibel, dB.

3.11 Transmitting response to current of a projector

At a given frequency and in a specified direction, the ratio of the sound pressure at a reference distance from the acoustic centre of a projector, multiplied by that reference distance, to the current flowing through the electrical terminals.

Reference distance is 1 m.

Symbol: S .

Unit: pascal metre per ampere, Pa m/A.

3.11.1 transmitting response level

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

Unit: decibel, dB.

NOTE S_{ref} is equal to 1 $\mu\text{Pa m/A}$.

3.12 electrical terminals of a reciprocal transducer

those terminals where the open circuit hydrophone voltage is measured, as well as the projector current

NOTE If the transducer is immersed in water, the terminal with the lowest impedance with respect to water is called the "low terminal". Consequently, the other terminal is called the "high terminal" (see Sub-clause 6.3.2).

3.13 electrical impedance of a transducer

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

Symbol: Z .

Unit: ohm, Ω .

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

3.14 electrical transfer impedance magnitude of a transducer pair

the ratio of the open circuit voltage U_H across the hydrophone terminals to the 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

Symbol: $|Z_{PH}|$.

$$\left| Z_{PH} \right| = \frac{U_H}{I_p} \quad (3.1)$$

Unit: ohm, Ω .

NOTE 1 Definition of principal axis is given in Sub-clause 3.20.

NOTE 2 Because this impedance magnitude depends on the field conditions and the electrical load conditions of the projector and the hydrophone, these conditions as well as the terminals where the voltage and the current are measured, shall be 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 acoustic centres of the projector and the hydrophone:

$$Z_{\text{PH}} d = \text{constant} \quad (3.2)$$

3.15

pistonphone

an 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 10 (under consideration)

3.16

vibrating column

an instrument 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 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 must be small compared with its length.

see Clause 11 (under consideration)

3.17

equivalent noise pressure

the sound pressure that must be applied at the hydrophone to cause a voltage at the hydrophone terminals equal to the noise voltage present at the same 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. See bibliography, reference [11]¹⁾.

3.18

dynamic range

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

3.19

directional response

a 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 acoustic centre and at a specified frequency (see Appendix D)

3.20

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.

3.21

omnidirectionality

if the response of a transducer shows variations smaller than a given limit as the direction is changed, the response is called “omnidirectional” within the given limit

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 acoustic centre.

¹⁾ References in these brackets refer to the bibliography, pages 40–43.

3.22

types of directional transducers

a transducer can be classified according to its directionality:

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

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

a DIPOLE transducer is bidirectional and has two axes in opposite directions

a FLAT PISTON transducer is unidirectional and has one axis, generally perpendicular to the piston surface

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

see [55] to [59]

3.23

co-ordinate system

the directivity pattern shall be plotted in reference to a “left-hand” co-ordinate system (see Figure 1) in the following way:

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.

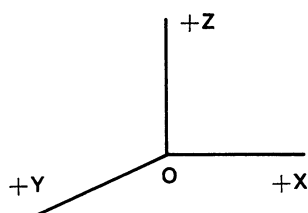


Figure 1 — “Left-hand” co-ordinate system

see [11]

see Appendix D

4 Procedures for calibration

4.1 Principles

Procedures for the calibration of hydrophones are specified by the following principles:

1) Calibration without a standard transducer

This type of calibration covers:

a) Reciprocity calibration

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

b) Physical calibration

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

2) Calibration with a standard transducer

A hydrophone or a projector can be calibrated by comparison with a calibrated standard hydrophone. In the latter case, the calibrated projector can be used to calibrate another hydrophone.

4.2 Field limitations

According to the limitations of the sound field, two types of calibration can be distinguished:

1) *Free field calibration*

The boundaries of the sound field are such that calibration is possible in free field conditions (see Sub-clause 3.1).

2) *Small chamber calibration*

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 Sub-clauses 9.6 and 9.7).

4.3 Schematic survey of procedures

Considerations of the different principles and of the limitations in the sound field and in the frequency range lead to the following different procedures:

- | | |
|---|-----------------------|
| 1) Free field reciprocity calibration | Clause 7 |
| — calibration without a standard transducer in a free field, between 1 kHz and 1 MHz. | |
| 2) Free field calibration by comparison | Clause 8 |
| — calibration with a standard transducer in a free field, between 100 Hz and 1 MHz. | |
| 3) Compensation in a closed chamber | Clause 9 |
| — physical calibration without a standard transducer in a closed chamber, between 0.1 Hz and 5 kHz. | |
| 4) Calibration with a pistonphone or a vibrating column | Clauses 10 and 11 |
| — physical calibration without a standard transducer in a small chamber, between 1 Hz and 3 kHz. | (under consideration) |

5 Preparation of the transducers

Prior to the actual calibration procedure, careful preparation of the transducers is necessary, as outlined in the following sub-clauses:

5.1 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 should be applied to the whole transducer surface. No dry patches should be visible on the transducer when it is immersed and then removed from the water.

5.2 Hydrophone support

The hydrophone should be supported in such a way that the sensitivity cannot be affected and structure borne noise cannot be picked up.

Suspension on thin wires or resilient mounting with rubber springs may offer a good way of support.

5.3 Influence of the cable

If the cable to the hydrophone must be lengthened for the purpose of the calibration, the capacitance of the extension cable is measured separately, in order to calculate the signal attenuation due to the extension. Cable lengths exceeding 0.1 wavelength at the highest frequency should be avoided.

6 Electrical measurements

6.1 Signal type

The signal used for the calibration may be either sinusoidal or filtered noise. The frequencies for sine wave signals are to be chosen with intervals not larger than one-third octave. According to ISO Standard 266, the following frequencies are recommended:

- 1.0 Hz; 1.25 Hz; 1.6 Hz; 2.0 Hz; 2.5 Hz; 3.15 Hz; 4.0 Hz; 5.0 Hz;
6.3 Hz; 8.0 Hz and 10.0 Hz and 10-fold multiples of this series.

However, if resonance occurs, closer spaced frequency points have to be chosen.

Filtered noise will be taken from a noise generator producing pink noise. Pink noise is defined as having a power spectral density inversely proportional to frequency. Therefore, the power in a band (f_1, f_2) is proportional to $\ln(f_2/f_1)$.

6.2 Earthing

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

6.3 Measurement of hydrophone output voltage

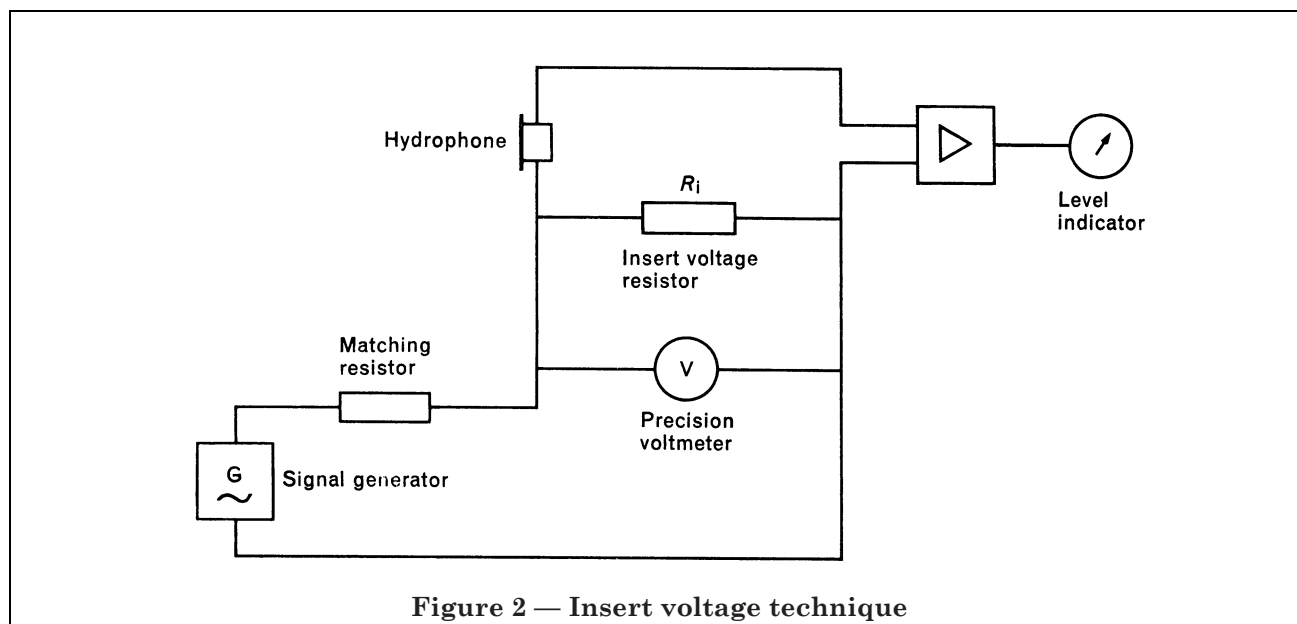
6.3.1 Direct measurement

The open circuit voltage of the hydrophone can be measured directly with the aid of a calibrated voltmeter, having an input impedance at least 100 times the electrical impedance at the hydrophone terminals. The voltmeter shall be calibrated with an accuracy better than 1 %.

6.3.2 Insert voltage technique

The insert voltage technique is used to determine the open circuit voltage of a hydrophone when it is electrically loaded or when the gain of the amplifier chain is uncertain (see Figure 2, page 8).

A small resistor R_i , usually in the range of 1 Ω to 100 Ω , is connected in series with the low terminal of the hydrophone, and a known calibration voltage is applied across it. Let a sound pressure and a calibration voltage of the same frequency be applied alternately. When the calibration voltage is adjusted until it gives the same level reading as that which results from the sound pressure on the hydrophone, the open circuit voltage will be equal in magnitude to the calibrating voltage.



The accuracy of the voltmeter shall be better than 1 %.

NOTE 1 If the hydrophone is equipped with a built-in preamplifier, connected by a long cable to a measuring station, it is a matter of convenience not to measure the insert voltage directly, but to measure the current flowing through R_i . In that case, the accuracy of R_i shall be better than 1 %.

Reference is made to IEC Publication 500, IEC Standard Hydrophone.

NOTE 2 The impedance due to the capacitance between the cable leads, combined with the capacitance of each cable lead to ground, must be higher than 100 R_i .

NOTE 3 The insert voltage technique also enables the pre-amplifier gain to be measured.

NOTE 4 The matching resistor in Figure 2 serves to match the relatively low resistance of R_i to the usually required higher load resistance of the signal generator.

6.3.3 Noise

The level of the noise or other interference such as crosstalk, whether of acoustical or electrical origin, shall be at least 20 dB lower than the signal level. In the case of a continuous signal the crosstalk level shall be at least 40 dB lower than the signal level.

See [10], [31] and [32].

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

6.4 Measurement of projector current

6.4.1 Direct measurement

The projector current can be measured directly by means of a calibrated current meter, connected in series with the low terminal of the projector.

This current meter shall be calibrated with an accuracy of better than 1 %. If the current meter is inserted in series with the high terminal of the projector, care must be taken to avoid stray impedance to earth that shunts the impedance of the projector.

6.4.2 Indirect measurement

A small resistor R_c , usually in the range 1 Ω to 100 Ω , is connected in series with the low terminal of the projector. The projector current flowing through this resistor produces a voltage that is proportional to the projector current. This voltage is measured with a calibrated voltmeter.

When one side of the series resistor is connected to earth, either the projector or the output circuit of the power amplifier will be “above earth”.

The precision of the resistor, as well as the accuracy of the voltmeter shall be better than 1 %.

The impedance to ground that shunts the current measuring resistor R_c must be greater than 100 R_c .

6.5 Measurement of transfer impedance magnitude

6.5.1 Indirect method

The magnitude of the transfer impedance of a transducer pair can be calculated as the open circuit hydrophone voltage U divided by the projector current I (see Sub-clause 3.14).

6.5.2 Differential method

If the projector current is measured indirectly with the aid of a known series resistance (see Sub-clause 6.4.2), the open circuit hydrophone voltage can be measured with the same voltmeter that is used to measure the voltage drop across that resistor. In this case, the voltmeter needs no absolute calibration. The attenuator of that voltmeter, as well as the meter scale, shall have an accuracy better than 1 %.

Care must be taken to avoid changes in ground connections if the voltmeter is switched from the projector circuit to the hydrophone circuit.

6.5.3 Substitution method

If the projector current is measured by means of a known series resistance (see Sub-clause 6.4.2) and the open circuit hydrophone voltage with the insert voltage technique (see Sub-clause 6.3.2), determination of the transfer impedance magnitude is possible without a calibrated voltmeter, using the substitution method (see Appendix A).

6.5.4 Direct read-out method

The transfer impedance magnitude can be transformed to a voltage ratio by means of a precision resistor and a differentiating circuit introduced in the chain of a reversible transducer. By this method the hydrophone sensitivity is determined by reading of calibrated attenuators only (see Appendix B).

NOTE This method is convenient to calibrate many hydrophones in a short time. However, careful attention must be paid to accuracy and reliability of the complicated electrical circuit.