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INTERNATIONAL STANDARD

NORME INTERNATIONALE

AMENDMENT 2
AMENDEMENT 2

Ultrasonics – Hydrophones –
Part 2: Calibration for ultrasonic fields up to 40 MHz

Ultrasons – Hydrophones –
Partie 2: Etalonnage des champs ultrasoniques jusqu'à 40 MHz

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FOREWORD

This amendment has been prepared by IEC technical committee 87: Ultrasonics.

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

CDV	Report on voting
87/612/CDV	87/639/RVC

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

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

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- withdrawn,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

2 Normative references

Add the following new reference:

IEC 61689, *Ultrasonics – Physiotherapy systems – Field specifications and methods of measurement in the frequency range 0,5 MHz to 5 MHz*

3 Terms, definitions and symbols

3.26
derived instantaneous intensity
(added by Amendment 1)

Delete the following text below the term:

"approximation of the **instantaneous intensity**"

Replace the existing four lines before Equation (1) by the following:

quotient of squared instantaneous acoustic pressure and characteristic acoustic impedance of the medium at a particular instant in time at a particular point in an acoustic field

4 List of symbols

Replace:

ρc specific acoustic impedance

by

ρc characteristic acoustic impedance of the measurement liquid (water)

Add the following new symbols:

d_1 distance between the auxiliary transducer and the reflector measured along the axis of symmetry

d_h distance between the auxiliary transducer and the active element of the hydrophone measured along the axis of symmetry

d_m distance between the auxiliary transducer and the last minimum of the acoustic pressure amplitude along the axis of symmetry of the auxiliary transducer

R_{RT} amplitude reflection coefficient for the reflector/water interface

Z_{RT} characteristic acoustic impedance of the reflector

J_p reciprocity coefficient for plane waves

S_t^* apparent transmitting current response of an auxiliary transducer

M_t^* apparent receiving voltage response of an auxiliary transducer

p_a acoustic pressure generated by a transducer at its surface

p_i acoustic pressure incident on a transducer surface

p_h acoustic pressure incident on the hydrophone surface

I_t transmitting current driven to a transducer

U_t voltage generated by a transducer in the receiving mode

G_{th} correction that accounts for the diffraction in the propagation field and is related to the waveform generation by the transducer and the reception by the hydrophone

G_{tt} correction that accounts for the diffraction in the propagation field and is related to the generation and the reception by the transducer

U_{load} voltage measured with the transducer coupled to the system

I_{sc} current measured over a short circuit jumper replacing the transducer

9 Free field reciprocity calibration

9.1 General

Replace the existing text by the following:

This clause specifies the primary reference measurement procedure (see JCGM 200:2012, 2.8 [79]) calibration of **hydrophones** under **free field** conditions using the principle of reciprocity.

Add the following new note:

NOTE The free field condition can be achieved in a confined water space by following any of a variety of measurement procedures, such as with the use of tone-burst (time-gated sine wave – see 10.5.3), time-delay spectrometry [63, 68], frequency modulated chirp [80, 81] or other techniques [82].

9.4 Two-transducer reciprocity calibration method

9.4.1 Apparatus

Replace the existing subclause title and text by the following:

9.4.1 Auxiliary transducers

Circularly plane piston auxiliary transducers should be used to generate the ultrasonic field in the frequency range of interest, limited to the maximum range between 1 MHz and 15 MHz. The effective radiation area (A_{ER}) shall be determined, according to IEC 61689, for each transducer and at all frequencies the transducer is intended to be used. If a frequency modulated chirp is to be used as excitation signal, the A_{ER} shall be determined at least in the minimum, maximum and one intermediate frequency in the range of interest.

The position of the last minimum of acoustic pressure amplitude along the axis of symmetry, d_m, shall be determined with an uncertainty not larger than 1 mm. It shall be done as an on-axis line scan, according to IEC 61689, at the same frequencies the A_{ER} was determined. The near field distance produced by the auxiliary transducer is defined as $N_1 = a_t^2/\lambda$, where λ is the ultrasonic wavelength in water at the frequency of operation and $a_t = \sqrt{2\lambda d_m + \lambda^2}$ is the effective radius of the ultrasonic transducer.

NOTE Focusing auxiliary transducers can be used, but several corrections need to be applied, and this document is only intended for plane-piston transducers. A detailed implementation of a reciprocity-based calibration method using focusing transducers can be found in [84].

The effective radiation area (A_{ER}) is used in the equations of Annex K to properly assess the diffraction correction and the reciprocity coefficient for plane waves, whilst the last minimum of pressure amplitude along the axis of symmetry (d_m) is used to indirectly define the near field distance (N_1), being $N_1 = (2\lambda d_m + \lambda^2)/\lambda$. Although both quantities A_{ER} and d_m are directly linked for ideal transducers, both shall be determined experimentally according to IEC 61689.

9.4.2 Procedure

Replace the existing subclause title and text by the following:

9.4.2 Reflector

The reflector should comprise a flat surface whose smallest linear dimension shall be at least four times the effective radius of the ultrasonic transducer a_t. The reflector shall also be flat to ±10 µm, with a surface finish good to ±5 µm (surface roughness: R_v < 5 µm; R_p < 5 µm; R_a < 1 µm). The thickness of the reflector shall be such that the first reflection from the rear surface will not interfere with that directly from the front surface for any of the excitation signals to be used. Special attention shall be given for long burst or low-rate frequency modulated chirps, mainly at the lowest frequencies of interest.

The amplitude reflection coefficient for the reflector/water interface R_{RT} shall be experimentally determined, for instance by the relation $R_{RT} = (Z_{RT} - \rho c)/(Z_{RT} + \rho c)$, were ρc is the characteristic acoustic impedance of the water and Z_{RT} is the characteristic acoustic impedance of the reflector.

NOTE R_v is the maximum valley depth, R_p is the maximum peak height and R_a is the arithmetic average describing the reflector profile roughness amplitude parameters.

Add the following new subclauses:

9.4.3 Measurement field

As both the auxiliary transducer and the **hydrophone** have finite apertures, a diffraction pattern is present in the ultrasonic field. To minimize uncertainties due to the analytical or numerical corrections to be applied to the measurement quantities, the nearest measurement shall be performed at least at 0,9 × N_1, and the furthest distance shall not be larger than 2,2 × N_1. Water-air surface and tank walls shall be far enough from the ultrasonic path such that any reflected waveform will not interfere with the direct waveform at the measurement spot.

If any structure is too close to the direct ultrasonic waveform path, it shall be covered with absorbing lining to minimize the interference with the measurement signal, and concern about that interference shall be included in the uncertainty budget.

9.4.4 Reciprocity approach

Reciprocity can be established as a primary **hydrophone** calibration method provided some practical and theoretical details are adopted. Annex K depicts the fundamentals of the reciprocity approach.

9.4.5 Measurement procedure

Several distinct setups (see Annex K [83, 84, 85]) could be used regarding the positioning of the three main elements of the two-transducer reciprocity calibration method: auxiliary transducer, reflector and **hydrophone**.

Regardless of the configuration adopted, the self-calibration of the auxiliary transducer is the first step, and it is done to quantify the acoustic pressure generated by the transducer in a defined spot in the ultrasonic field.

Annex K
(informative)

Two-transducer reciprocity calibration method

Replace the existing Annex K, added by Amendment 1, by the following:

K.1 General

The two-transducer reciprocity method involves the assessment of the acoustic pressure in a defined spot in the ultrasonic field. To accomplish that, the first step is to assess the ultrasonic field generated by an auxiliary transducer. The second step is to place the active element of the **hydrophone** to be calibrated in a defined spot for which the acoustic pressure can be defined as precisely as possible.

K.2 Fundamentals of reciprocity

A reversible transducer has an apparent transmitting current response $S_t^*(\omega)$ and apparent receiving voltage response $M_t^*(\omega)$ defined as

$$S_t^* = \frac{p_0(\omega)}{I_t(\omega)} \text{ and } M_t^* = \frac{U_t(\omega)}{p_i(\omega)} \tag{K.1}$$

where p_0 is the acoustic pressure generated by the auxiliary transducer at its surface, I_t is the transmitting current of the transducer, p_i is the acoustic pressure incident on the transducer surface and U_t is the voltage generated by the transducer in the receiving mode.

NOTE The term ‘acoustic pressure’ is used in Annex K, although it is recognized that in any practical situation this quantity will vary spatially. Similarly, the electrical output of transducer devices used in reception mode will be dependent on the acoustic pressure spatially-averaged on their active surface.

If the transducer is reciprocal, the reciprocity coefficient for plane waves J_p relates $S_t^*(\omega)$ and $M_t^*(\omega)$ as follows:

$$J_p = \frac{M_t^*(\omega)}{S_t^*(\omega)} \tag{K.2}$$

By definition, $J_p = \frac{2A_{ER}}{\rho c} J_p = \frac{2A_{ER}}{\rho c}$.

If the wave generated by a reciprocal transducer propagates in water and reflects off with a normal incidence at a reflector distant d_1 from the transducer surface placed on its axis of symmetry, it produces an incident wave whose acoustic pressure can be measured by the reciprocal transducer. Relating the definition by Equation (K.3)

$$p_i(\omega) = p_0(\omega) R_{RT} e^{-2\alpha d_1} G_{tt} \tag{K.3}$$

where α is the amplitude attenuation coefficient of plane waves in water and G_{tt} is the correction due to the fact that the returning waveform is generated and measured by a finite transducer, i.e. it accounts for the diffraction in the propagation field and is related to the generation and reception by the transducer. Combining Equations (K.1), (K.2) and (K.3), the acoustic pressure generated by a reciprocal transducer at its surface is related to electrical and geometrical quantities as follows:

$$p_0(\omega) = \sqrt{U_t(\omega) I_t(\omega) \frac{\rho c}{2 A_{ER} R_{RT} e^{-2\alpha d_1} G_{tt}}} \; . \tag{K.4}$$

A normal incidence reflection on the reflector is necessary for the self-calibration. This is ensured by maximizing the waveform reflection from the reflector as measured by the transducer. The driven electrical current I_t is measured with the auxiliary transducer in the output mode. The input voltage U_t is measured when the auxiliary transducer is in the input mode. It should be an open-circuit voltage, and electrical corrections should be applied to the measured current and voltage.

In sequence, the **hydrophone** active element is placed in a determined spot in the ultrasonic field, and the acoustic pressure is maximized in order to assure the alignment of the **hydrophone** active element symmetry axis and the transducer symmetry axis. The acoustic pressure at this point is calculated using the following expression:

$$p_h(\omega) = p_0(\omega) e^{-\alpha d_h} G_{th} \tag{K.5}$$

where p_h is the measured acoustic pressure incident on the **hydrophone's** active element if the **hydrophone** were removed, d_h is the distance from the transducer surface to the active hydrophone element measured on the symmetry axis, and G_{th} is the correction that accounts for the diffraction in the propagation field and is related to the generation transducer and the reception by the **hydrophone**.

The open-circuit voltage from the **hydrophone** U_h should be measured with p_h incident on its active element. The end of cable sensitivity is therefore given as

$$M(\omega) = \frac{U_h(\omega)}{p_h(\omega)} \tag{K.6}$$

K.3 Electrical quantities

The transmitting current, I_t, shall be measured as precisely as possible, which can be performed in many different ways. Measuring the voltage drop across a calibrated impedance or using a current probe are typical electrical setups.

The output voltage from the transducer in the receiving mode, U_t, shall be measured unloaded by the transducer, i.e. as an open circuit voltage. One way to perform that is to measure the current over a short circuit replacing the transducer. The open circuit voltage is

$$U_t(\omega) = U_{load}(\omega) \frac{I_{sc}(\omega)}{I_t(\omega)} \tag{K.7}$$

where U_{load} is the voltage measured with the transducer coupled to the system and I_{sc} is the current measured over a short circuit jumper replacing the transducer.

In the case of a constant load assumed throughout the calibration process, corrections described in Annex C could be applied directly to the final assessed sensitivity.

K.4 Diffraction correction and loss due to nonlinear sound propagation

Due to the finite size of auxiliary transducers and **hydrophones**, a diffraction pattern develops in the ultrasonic field. In the two-transducer reciprocity method, two diffraction corrections are applied: G_{th}, correction that accounts for the diffraction in the propagation field and is related to the waveform generation by the transducer and the reception by the **hydrophone**, and G_{tt}, correction due the generation and the reception by the transducer. Many references can be used to theoretically describe the diffraction loss in ultrasonic fields [83, 86, 87], and a numerical implementation of diffraction corrections can be applied [88, 89, 90, 91].

K.5 Ultrasonic field

For the two-transducer reciprocity calibration, the ultrasonic field is shaped by the influence of many aspects, mainly:

- diffraction pattern for both the auxiliary transducer and hydrophone (see K.3);
- signal type (see Annex G and [8, 80]);
- reflector reflection coefficient (see 9.4.2);
- water path attenuation (see [92]);
- speed of sound (see [36]).

The amplitude attenuation coefficient for plane ultrasonic waves, α, in the megahertz frequency range is proportional to f^2, and should be taken from a polynomial fit as a function of temperature T in the temperature range from 0 °C to 60 °C [92]:

$$\alpha / f^2 = \begin{pmatrix} 5{,}685 \cdot 10^{1} - 3{,}025 \cdot 10^{0} \{T\} \\ + 1{,}174 \cdot 10^{-1} \{T\}^2 - 2{,}954 \cdot 10^{-3} \times \{T\}^3 \\ + 3{,}970 \cdot 10^{-5} \{T\}^4 - 2{,}111 \cdot 10^{-7} \{T\}^5 \end{pmatrix} \times 10^{-15}\,\mathrm{Hz}^{-2} \cdot \mathrm{m}^{-1} \qquad \text{(K.8)}$$

NOTE 1 $\{T\}$ denotes the numerical value of the temperature in °C.

NOTE 2 If the amplitude attenuation coefficient in m^{-1} is going to be given in dB m^{-1}, its numerical value should be multiplied by $20 \cdot \log_{10}(\mathrm{e}) = 8{,}69$.

The speed of sound is presented in tables in [36], and polynomial fits are available for different accuracies, temperature ranges, and barometric pressures. The contribution for the uncertainty budget should be taken into account regarding the formula used to assess the speed of sound.

a) Temperature range: 0 °C to 100 °C at atmospheric pressure; accuracy better than 0,02 ms^{-1} (see [93])

$$c = \begin{pmatrix} 1402{,}39 + 5{,}03836\,\{T\} - 0{,}0581173\,\{T\}^2 \\ + 3{,}34638 \cdot 10^{-4} \{T\}^3 - 1{,}48260 \cdot 10^{-6} \{T\}^4 \\ + 3{,}16585 \cdot 10^{-9} \{T\}^5 \end{pmatrix} \mathrm{m} \cdot \mathrm{s}^{-1} \qquad \text{(K.9)}$$

b) Temperature range: 10 °C to 40 °C at atmospheric pressure; accuracy better than 0,18 ms^{-1} (see [93])

$$c = \left(1405{,}03 + 4{,}624\,\{T\} - 0{,}0383\,\{T\}^2\right) \mathrm{m} \cdot \mathrm{s}^{-1} \qquad \text{(K.10)}$$

c) Temperature range: 15 °C to 35 °C at atmospheric pressure; accuracy better than 0,20 ms^{-1} (see [94])

$$c = \left(1404{,}3 + 4{,}7\ \{T\} - 0{,}04\ \{T\}^2\right) \mathrm{m \cdot s^{-1}} \tag{K.11}$$

For the atmospheric pressure dependence of the speed of sound, see [95].

K.6 Experimental setup

K.6.1 General

Different experimental arrangements have been proposed to perform the two-transducer reciprocity calibration. Regardless of the electrical setup, the main concern in the experimental preparation comprises the positioning of the auxiliary transducer, reflector, and **hydrophone**. Three experimental setups are shown, each of them presenting advantages and drawbacks.

K.6.2 Twisting reflector

Figure K.1 depicts an arrangement in which the reflector is twisted between the two steps of the calibration procedure. Care should be taken to avoid a large angle of rotation of the reflector. A maximum of 10° would be acceptable, but the uncertainty of the **hydrophone** voltage measurement due to non-normal reflection should be considered. Moreover, for large membrane **hydrophones**, it could be a negative issue to set the rotation angle small. Another negative aspect of this arrangement is that it may not be simple to rotate large and heavy stainless steel reflectors with appropriate accuracy.

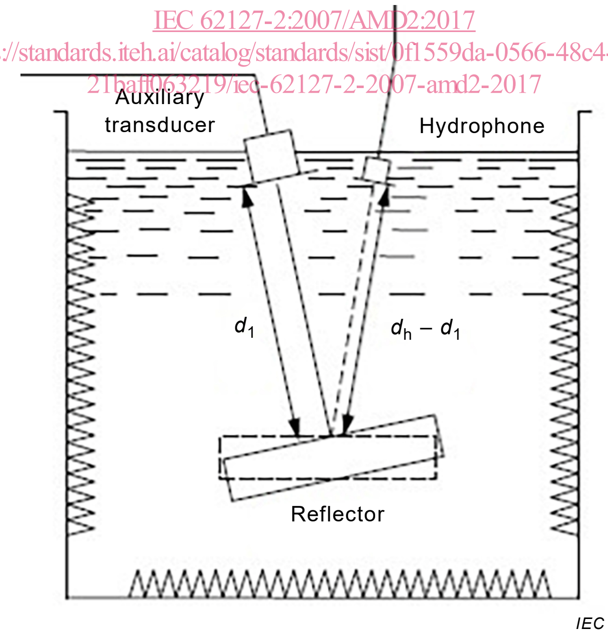

Figure K.1 – Experimental setup with a twisting reflector [83]

K.6.3 Translational reflector

Figure K.2 discloses an arrangement in which the reflector is inserted in the path between the auxiliary transducer and the **hydrophone**.

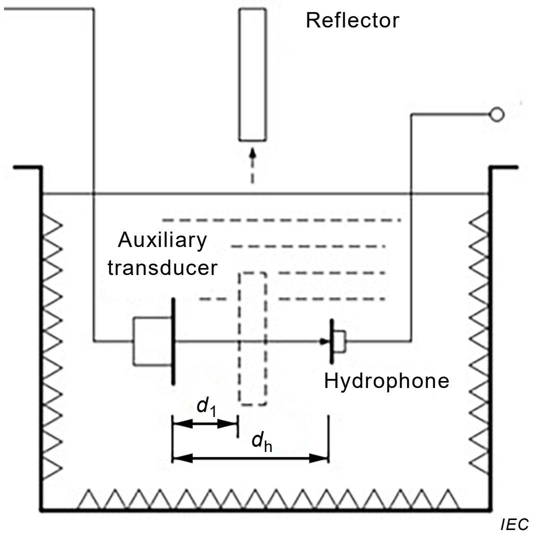

Figure K.2 – Experimental setup with a translational reflector [84]

K.6.4 Translational auxiliary transducer

In Figure K.3, the **hydrophone** and the reflector remain still during the measurement procedure, and the moving element is the transducer.

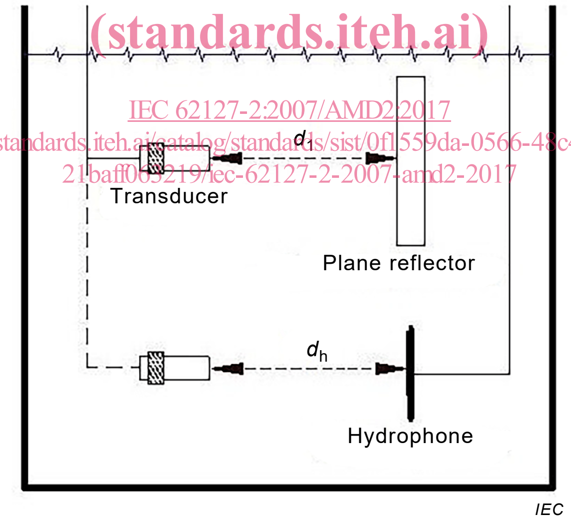

Figure K.3 – Experimental setup with a translational auxiliary transducer [85]