IEC TS 62903

Edition 1.0 2018-01

TECHNICAL SPECIFICATION

Ultrasonics – Measurements of electroacoustical parameters and acoustic output power of spherically curved transducers using the self-reciprocity method

IEC TS 62903:2018-01(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

IEC Catalogue - webstore.iec.ch/catalogue
The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and also once a month by email.

Electropedia - www.electropedia.org
The world's leading online dictionary of electronic and electrical terms containing 21 000 terms and definitions in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
67 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC TS 62903

Edition 1.0 2018-01

TECHNICAL SPECIFICATION

Ultrasonics – Measurements of electroacoustical parameters and acoustic output power of spherically curved transducers using the self-reciprocity method

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.140.50

ISBN 978-2-8322-5026-6

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD ... 5
INTRODUCTION ... 7
1 Scope ... 8
2 Normative references ... 8
3 Terms and definitions ... 8
4 Symbols ... 12
5 General ... 13
6 Requirements of the measurement system ... 14
6.1 Apparatus configuration ... 14
6.2 Measurement water tank ... 14
6.3 Fixturing, positioning and orientation systems ... 14
6.4 Reflector ... 14
6.5 Current monitor (probe) ... 14
6.6 Oscilloscope ... 15
6.7 Measurement hydrophone ... 15
7 Measurement of the effective half-aperture of the spherically curved transducer ... 15
7.1 Setup ... 15
7.2 Alignment and positioning of the hydrophone in the field ... 15
7.3 Measurements of the beamwidth and the effective half-aperture ... 15
7.4 Calculations of the focus half-angle and the effective area ... 16
8 Measurements of the electroacoustical parameters and the acoustic output power ... 16
8.1 Self-reciprocity method for transducer calibration ... 16
8.1.1 Experimental procedures ... 16
8.1.2 Criterion for checking the linearity of the focused field ... 16
8.1.3 Criterion for checking the reciprocity of the transducer ... 16
8.2 Calculations of the transmitting response to current (voltage) and voltage sensitivity ... 17
8.3 Calculations of the transmitting response at geometric focus to current (voltage) ... 17
8.4 Calculation of the pulse-echo sensitivity level ... 18
8.5 Measurements of the radiation conductance and the mechanical quality factor Q_m ... 18
8.5.1 Calculations of the acoustic output power and the radiation conductance ... 18
8.5.2 Measurement of the frequency response of the radiation conductance ... 18
8.6 Measurement of the electroacoustic efficiency ... 18
8.6.1 Calculation of the electric input power ... 18
8.6.2 Calculation of the electroacoustic efficiency ... 18
8.7 Measurement of the electric impedance (admittance) ... 19
9 Measurement uncertainty ... 19
Annex A (informative) Relation of the average amplitude reflection coefficient on a plane interface of water-stainless steel and the focus half-angle for a normally incident beam of a circular spherically curved transducer [1, 2] ... 20
Annex B (informative) Diffraction correction coefficient G_{sf} in the free-field self-reciprocity calibration method for circular spherically curved transducers in water neglecting attenuation [2, 3, 4] ... 24

Annex C (informative) Calculation of the diffraction correction coefficient $G_{sf}(R/\lambda,\beta)$ in the free-field self-reciprocity calibration in a non-attenuating medium for a circular spherically curved transducer [2, 3, 4, 7] ... 26
Annex D (informative) Speed of sound and attenuation in water ... 28
D.1 General ... 28
D.2 Speed of sound for propagation in water ... 28
D.3 Acoustic attenuation coefficient for propagation in water ... 28
Annex E (informative) Principle of reciprocity calibration for spherically curved transducers [2, 3, 4] ... 29
E.1 Principle of reciprocity calibration for an ideal spherically focused field of a transducer ... 29
E.2 Principle of reciprocity calibration of a real spherically focused field of a transducer ... 30
E.3 Self-reciprocity calibration of a spherically curved transducer ... 30
Annex F (informative) Experimental arrangements ... 35
F.1 Experimental arrangement for determining the effective radius of a transducer [2, 3, 4, 13] ... 35
F.2 Experimental arrangement of the self-reciprocity calibration method for a spherically curved transducer [2, 3, 4, 13] ... 35
Annex G (informative) Relationships between the electroacoustical parameters used in this application [13] ... 37
G.1 Relations between the free-field transmitting response to voltage (current) and the voltage sensitivity with the radiation conductance ... 37
G.2 Relation of the radiation conductance and the electroacoustic efficiency ... 38
G.3 Relation of the transmitting response and voltage and acoustic output power ... 38
G.4 Relation of the pulse echo sensitivity and the radiation conductance ... 38
Annex H (informative) Evaluation and expression of uncertainty in the measurements of the radiation conductance ... 39
H.1 Executive standard ... 39
H.2 Evaluation of uncertainty in the measurement of the radiation conductance ... 39
H.2.1 Mathematical expression ... 39
H.2.2 Type A evaluation of standard uncertainty ... 40
H.2.3 Type B evaluation of standard uncertainty ... 40
H.2.4 Evaluation of the combined standard uncertainty for the radiation conductance ... 42
Bibliography ... 46

Figure A.1 – Relation curve of the amplitude reflection coefficient $r(\theta_i)$ on the interface of water-stainless steel for a plane wave with the incident angle θ_i ... 22
Figure A.2 – Average amplitude reflection coefficient $r_{av}(\beta)$ on the plane interface of water-stainless steel in the geometric focal plane of a spherically curved transducer vs. the focus half-angle β ... 23
Figure C.1 – Geometry of the concave radiating surface A of a spherically curved transducer and its virtual image surface A' for their symmetry of mirror-images about the geometric focal plane $(x,y,0)$ ... 26
Figure E.1 – Spherical coordinates ... 31
Figure E.2 Function $G_a(ka\sin\theta)$, diffraction pattern $F_0(ka\sin\theta)$ and $F_0{}^2(ka\sin\theta)$ in the geometric focal plane [7] ... 32
Figure F.1 – Scheme of the measurement apparatus for determining the effective half-aperture of a transducer ... 35

Figure F.2 – Scheme of free-field self-reciprocity method applied to a spherically curved transducer 36

Table A.1 – Parameters used in calculation of the average amplitude reflection coefficient 21
Table A.2 – Amplitude reflection coefficient $r(\theta_i)$ on a plane interface of water-stainless steel for plane wave vs. the incident angle θ_i 21
Table A.3 – Average amplitude reflection coefficient $r_{av}(\beta)$ on plane interface of water-stainless steel in the geometric focal plane of a spherically curved transducer vs. the focus half-angle β 22
Table B.1 – Diffraction correction coefficients G_{sf} of a circular spherically curved transducer in the self-reciprocity calibration method [2, 3, 4] 24
Table D.1 – Dependence of speed of sound in water on temperature [5] 28
Table E.1 – G_a values dependent on $ka\sin\theta$ for $\beta \leq 45°$ where $x = ka\sin\theta$ (according to O'Neil [7]) 32
Table E.2 – The $(R/\lambda)_{min}$ values dependent on β when $\theta_{max} \geq \theta_{Ga}$ and $\beta < 45°$ for G_a = 0,94; 0,95; 0,96; 0,97; 0,98; 0,99 33
Table H.1 – Type B evaluation of the standard uncertainties (SU) of input quantities in measurement 41
Table H.2 – Components of the standard uncertainty for the measurement of the radiation conductance using the self-reciprocity method 44
Table.H.3 – The measurement results and evaluated data of uncertainty for five transducers 45

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ULTRASONICS – MEASUREMENTS OF ELECTROACOUSTICAL PARAMETERS AND ACOUSTIC OUTPUT POWER OF SPHERICALLY CURVED TRANSDUCERS USING THE SELF-RECIPROCITY METHOD

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62903, which is a Technical Specification, has been prepared by IEC technical committee 87: Ultrasonics.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
87/652/DTS	87/659/RVDTS

Full information on the voting for the approval of this technical specification 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.

In this standard, the following print types are used:

- **terms defined in Clause 3: in bold type**.

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.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

An ultrasonic transducer is an important acoustic device that can act as a transmitter or a receiver in the applications of medical ultrasound, non-destructive testing, and ultrasonic materials processing. The performance of a transducer is a decisive factor that governs the device's range of applicability, efficiency and quality control in the manufacturing. The mechanisms, transmitting fields, performances, and measurement methods used for these transducers have been studied over the past few decades. However, the electroacoustical characterization and measurement methods applied for spherically curved transducers have not been defined in standard documents for either terms or protocols.

This document defines the relevant electroacoustical parameters for these devices and establishes the self-reciprocity measurement method for spherically curved concave focusing transducers.

ULTRASONICS – MEASUREMENTS OF ELECTROACOUSTICAL PARAMETERS AND ACOUSTIC OUTPUT POWER OF SPHERICALLY CURVED TRANSDUCERS USING THE SELF-RECIPROCITY METHOD

1 Scope

This document, which is a Technical Specification,

a) establishes the free-field convergent spherical wave self-reciprocity method for ultrasonic transducer calibration,

b) establishes the measurement conditions and experimental procedure required to determine the transducer's electroacoustic parameters and acoustic output power using the self-reciprocity method,

c) establishes the criteria for checking the reciprocity of these transducers and the linear range of the focused field, and

d) provides guiding information for the assessment of the overall measurement uncertainties for radiation conductance.

This document is applicable to:

i) circular spherically curved concave focusing transducers without a centric hole working in the linear amplitude range,

ii) measurements in the frequency range 0,5 MHz to 15 MHz, and

iii) acoustic pressure amplitudes in the focused field within the linear amplitude range.

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 60050-801:1994, *International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-801:1994 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
p_{av}
average acoustic pressure
acoustic pressure averaged over the **effective area** of the transducer

Note 1 to entry: **Average acoustic pressure** is expressed in pascals (Pa).

3.2
$r_{av}(\beta)$
average amplitude reflection coefficient
ratio of the **free-field** echo **average acoustic pressure** $p_{av}(\beta)$ reflected by the reflector on the geometric focal plane over the space area coincident with the **effective area** of the spherically curved transducer of focus half-angle β, if the transducer were removed, to the **reference acoustic pressure** p_0 on the **effective area** of the transducer in a non-attenuation medium with negligible diffraction, $r_{av}(\beta) = p_{av}(\beta)/p_0$

3.3
G_{sf}
diffraction correction coefficient
ratio of the **average acoustic pressure** over the spherical segment surface of the spherically curved transducer's virtual image at a position in the distance of twice **geometric focal length** from the transducer, if an ideal reflecting mirror were located on the geometric focal plane, to the **reference acoustic pressure** of the transducer in the **free-field** of a non-attenuation medium

3.4
A
effective area
<transducer> area of the radiating surface of a theoretically predicted transducer with specific field distribution characteristics that are approximately the same as those of a real transducer of the same type

Note 1 to entry: For a spherically curved transducer, the theoretically predicted acoustic pressure distribution on the geometric focal plane of a transducer should be approximately the same as that of the real transducer with the same **geometric focal length** when operating at the same frequency.

Note 2 to entry: The half-aperture of an **effective area** is also named the effective half-aperture or the effective radius.

Note 3 to entry: The **effective area** of a transducer is expressed in metres squared (m^2).

3.5
$\eta_{a/e}$
electroacoustic efficiency
ratio of the acoustic output power to the electric input power

3.6
electroacoustical reciprocity principle
electroacoustical reciprocity theorem
principle that the ratio of the **free-field voltage (current) sensitivity** of a **reciprocal transducer** as a receiver, to the **transmitting response to current (voltage)** of the **reciprocal transducer** as a projector is constant

Note 1 to entry: This principle is independent of the construction of the **reciprocal transducer**.

3.7
free-field
sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on the sound wave

[SOURCE: IEC 61161:2013, 3.2]

3.8
M
free-field voltage sensitivity of a spherically curved transducer
receiving voltage response of a spherically curved transducer
ratio of the open-circuit output voltage of a spherically curved transducer within the field of a point source at the **geometric focus** to the **free-field** acoustic pressure acting on the space surface where the transducer surface was present, if that transducer were removed

Note 1 to entry: **Free-field voltage sensitivity of a spherically curved transducer** is expressed in volts per pascal (V/Pa).

3.9
geometric beam boundary
surface containing straight lines passing through the **geometric focus** and all points around the periphery of the transducer aperture

Note 1 to entry: The definition applies to transducers of known construction.

[SOURCE: IEC 61828:2006, 4.2.36]

3.10
F_{geo}
geometric focal length
distance from the **geometric focus** to the ultrasonic transducer's focusing surface

Note 1 to entry: The definition applies to transducers with known construction and is equal to the radius of curvature of the radiating surface.

Note 2 to entry: The focusing surface is the surface of constant phase, whose periphery is coincident with the transducer's aperture.

Note 3 to entry: **Geometric focal length** is expressed in metres (m).

3.11
geometric focus
point for which all of the effective path lengths in a specified longitudinal plane are equal

Note 1 to entry: The **geometric focus** is also the point for which all waves from the transducer have the same delay as viewed in the approximation of geometrical acoustics neglecting diffraction.

[SOURCE: IEC 61828:2006, 4.2.39, modified – In the definition, the added explanation for the definition "Also, the point for which all...diffraction." has been moved to a Note to entry.]

3.12
$L_{M\text{pe}}$
pulse-echo sensitivity level
ratio of the received open-circuit voltage for the first echo signal of the spherically curved transducer when acting as a receiver to the exciting voltage of the transducer when it is transmitting a tone burst ultrasonic beam in a direction perpendicular to an ideal plane reflector (r = 1) at the geometric focal plane

Note 1 to entry: The ratio is expressed in decibels (dB).

3.13
G
radiation conductance
ratio of the acoustic output power and the squared effective transducer input voltage

Note 1 to entry: It is used to characterize the electrical to acoustical transfer of ultrasonic transducers.

Note 2 to entry: The frequency of the input voltage (or current) should be noted.

Note 3 to entry: **Radiation conductance** is expressed in siemens (S).

[SOURCE: IEC 61161:2013, 3.8, modified – In the definition, "RMS" has been replaced with "effective".]

3.14
reciprocal transducer
linear, passive and **reversible transducer**

Note 1 to entry: An example of a non-**reciprocal transducer** is one that mixes a magnetic field device with an electric field device.

[SOURCE: IEC 60565:2006, 3.24]

3.15
J
reciprocity parameter
<transducer> ratio of the **free-field** voltage sensitivity of a transducer as a receiver to the **transmitting response to the current** of the transducer as a projector, or the ratio of the **free-field current sensitivity** of a transducer as a receiver to the **transmitting response to the voltage** of the transducer as a projector

Note 1 to entry: The **reciprocity parameter** of a spherically curved transducer, $J = J_{sf}$, is equal to the quotient of twice the **effective area** of the transducer divided by the acoustic characteristic impedance of the medium, i.e.

$$J_{sf} = 2A/(\rho\, c)$$

where

A is the **effective area** of curved surface of the spherically curved transducer;

ρ is the (mass) density of the medium;

c is the speed of sound in the medium (usually water).

Note 2 to entry: The **reciprocity parameter** is expressed in watts per pascal squared (W/Pa^2).

3.16
p_0
reference acoustic pressure
product of the uniform normal particle velocity on the spherically curved surface of the transducer and the characteristic impedance of the medium

Note 1 to entry: **Reference acoustic pressure** is expressed in pascals (Pa).

3.17
reversible transducer
transducer capable of acting as a projector as well as a receiver

[SOURCE: IEC 60565:2006, 3.26, modified – In the definition, "hydrophone" has been replaced with "receiver".]

3.18
self-reciprocity method
transducer calibration method based on the reciprocity principle that uses the received echo signal from the plane reflector that is set perpendicular to the incident beam axis of the transducer

3.19
S_I
transmitting response to current
transmitting current response
ratio of the **reference acoustic pressure** on the radiating surface of a transducer in the **free-field** in the absence of interference effects to the current flowing through the electrical terminals of a projector at a given frequency

Note 1 to entry: **Transmitting response to current** is expressed in pascals per ampere (Pa/A).

3.20
S_U
transmitting response to voltage
transmitting voltage response
the ratio of the **reference acoustic pressure** on the radiating surface of a transducer in the **free-field** in the absence of interference effects to the exciting voltage of a projector at a given frequency

Note 1 to entry: **Transmitting response to voltage** is expressed in pascals per volt (Pa/V).

4 Symbols

a	effective half-aperture, effective radius of transducer
A	**effective area** of transducer
c	speed of sound in sound propagating medium usually in water
d	distance from the centre of the transmitting surface of the transducer to the reflecting plane of the reflector in the geometric focal plane
f_0	resonant frequency
f_c	central frequency
F_{geo}	(= R) **geometric focal length**
G	**radiation conductance**
G_{sf}	**diffraction correction coefficient** for spherically curved transducer in free-field self-reciprocity calibration
h	height (depth) at the centre of a spherical segment
I	acoustic intensity
I_T, I_{Trms}	exciting current amplitude, effective exciting current
I_k	short-circuit current amplitude of the generator
I_{echo}	first echo current amplitude
J	**reciprocity parameter** of transducer
J_{sf}	**reciprocity parameter** of spherically curved transducer
k	(= $2\pi/\lambda$), circular wave number
k_m	ratio of the acoustic pressure at the **geometric focus** to the **reference acoustic pressure** on the radiation surface of the transducer
l	distance from the centre of receiving surface of the hydrophone to the centre of the transmitting surface of the transducer along their common axis after alignment
L_{Mpe}	**pulse-echo sensitivity level**
M	**free-field voltage sensitivity (receiving voltage response) of a spherically curved transducer**
p_0	**reference acoustic pressure** of a radiating surface
P	acoustic output power
P_e	electrical input power
q	(=(1 + cosβ)/2), ratio of the true time-average intensity I to the time-average derived intensity I_p at the **geometric focus**
Q_m	mechanical quality factor
r	amplitude reflection coefficient
$r_{av}(\beta)$	**average amplitude reflection coefficient** on a plane reflector in the geometric focal plane in water for a spherically curved transducer
R	radius of curvature

S_I	**transmitting response to current**
$S_{I\mathrm{f}}$	transmitting response at **geometric focus** to current
S_U	**transmitting response to voltage**
$S_{U\mathrm{f}}$	transmitting response at **geometric focus** to voltage
Δt_F	acoustic pulse transit time
U_0	open-circuit voltage amplitude of tone burst generator
U_T, U_Trms	exciting voltage amplitude, exciting effective voltage of the transducer
U_1	maximum of the first echo voltage amplitude received by the transducer to be calibrated in self-reciprocity calibration process
$U_{I\mathrm{T}}$	output voltage of the current probe picked up the exiting current of the transducer
$U_{I\mathrm{echo}}$	output voltage of the current probe picked up the first echo current of the transducer
$U_{I\mathrm{k}}$	output voltage of the current probe picked up the short-circuit current of the tone burst generator
U_rms	effective voltage
v	particle velocity
w_3	–3 dB beamwidth on geometric focal plane
w_6	–6 dB beamwidth on geometric focal plane
Y_T	electric admittance of transducer
Z_i	electric output impedance of generator
Z_T	electric impedance of transducer
α	acoustic attenuation coefficient in medium (usually in water)
β	(= arcsin(a/R)), focus half-angle
θ_e	electric impedance angle
ρ	(mass) density of the sound propagating medium (usually water)
$\eta_\mathrm{a/e}$	**electroacoustic efficiency**
λ	wavelength
τ	pulse duration

5 General

The transducer characteristics include the ultrasonic field parameters and the transmission and reception performance parameters.

The focused field performance parameters include the effective half-aperture (the effective radius), the beam width, the **effective area**, the **geometric focal length**, and the focus half-angle for spherically curved transducers.

The transmission performance parameters include the **radiation conductance**, the acoustic output power, the **free-field transmitting response to current (voltage)**, the **electroacoustic efficiency**, and the electric impedance.

The reception performance parameter is the **free-field voltage sensitivity**.

The transmission-reception parameter is the **pulse-echo sensitivity level.**

In this document, the beam profile method using a hydrophone is defined for the measurement of the field performance parameters; the **self-reciprocity method** is defined for the measurement of the **free-field transmitting response to current (voltage)**, the **free field voltage sensitivity, pulse-echo sensitivity level**, and the acoustic output power (see Annex E); the **radiation conductance** is derived from the acoustic power and the effective exciting voltage; the **electroacoustic efficiency** is calculated from the acoustic output power and the detected electrical input power. Relations between these electroacoustical parameters are given in Annex G.

6 Requirements of the measurement system

6.1 Apparatus configuration

The electrical system of the apparatus consists of a tone burst generator, a current monitor (probe), an oscilloscope and two switches. The acoustical system consists of a water tank for the measurements, a measurement hydrophone, fixtures, positioning and orientation systems (for both the transducer and the hydrophone), displacement sensors or indicators, and a stainless-steel reflector, as shown in Annex F. The apparatus for determining the effective radius and the self-reciprocity calibration are shown in Figures F.1 and F.2, respectively.

6.2 Measurement water tank

The tank shall have sufficient effective space of water bath to ensure that the maximum distance between the hydrophone and the transducer can be achieved to meet the requirements for fixtures, positioning and orienting the devices. The minimum dimensions of the tank for the tone burst field measurement only should be $(R + c\tau) \times (2Rc\tau + c^2\tau^2)^{1/2} \times (2Rc\tau + c^2\tau^2)^{1/2}$ (length × width × height), where R is the radius of curvature, c is the speed of sound in water, τ is the pulse duration and less than or equal to 30 cycles. Considering other requirements the tank should be not smaller than 0,55 m × 0,32 m × 0,38 m (length × width × height). The tank is filled with degassed water, and the water temperature is indicated by a thermometer.

6.3 Fixturing, positioning and orientation systems

The transducer and the hydrophone shall be fixed on fixtures that allow positional adjustment of the devices in three perpendicular directions as well as allowing their angles of azimuth and elevation to be independently and continuously being adjusted. The positioning accuracy should be better than ±0,1 mm in the axial direction z and ±0,01 mm in the lateral directions x and y, while the orientation accuracy should be better than ±0,05°. The resolution of the displacement sensor should be 0,01 mm or less.

6.4 Reflector

The reflector is a thick plate or cylinder made of stainless steel. One of the planes or terminal surfaces of the reflector is used as a reflection plane that should be flat to ±10 µm and should also show a surface finish good to ±5 µm. The thickness of the reflector shall be large enough to ensure that the first echo from the rear surface does not interfere with that from the front surface at the lowest frequency used. The reflector diameter shall be sufficient to reflect the entirety of the ultrasonic beam energy. The reflector diameter should be at least twice the −26 dB beam width or greater than the aperture of transducer whichever is the greater. The **average amplitude reflection coefficient** $r_{av}(\beta)$ is almost a constant 0,973 at the interface between water and stainless steel when the focus half-angle β is less than 13°. For other β values, $r_{av}(\beta)$ can be picked up from the data of Table A.2 in Annex A.

6.5 Current monitor (probe)

The frequency response of the current sensitivity of the monitor should be constant up to 1,4 times of the frequency of the current to be measured. The maximum detectable current should be greater than 1,5 times of the current to be measured. The rise time should be shorter than or equal to 20 ns. The accuracy should be better than or equal to ±1 %.

6.6 Oscilloscope

The bandwidth of the oscilloscope should be greater than or equal to 70 MHz. The resolution of voltage should be better than 1 mV. The error of voltage measurement should be less than or equal to ±2 %.

6.7 Measurement hydrophone

The maximum radius $a_{\text{h,max}}$ of the hydrophone active element should satisfy Formula (1):

$$a_{\text{h,max}} = \frac{\lambda}{8a}\sqrt{l^2 + a^2} \tag{1}$$

where l is the distance between the hydrophone and the transducer, a is the effective half-aperture of the transducer, and λ is the wavelength. The hydrophone used for the procedure does not need to be calibrated.

7 Measurement of the effective half-aperture of the spherically curved transducer

7.1 Setup

The transducer and the hydrophone are arranged in the water tank as shown in Figure F.1. A tone burst generator is used to excite the transducer directly or using a matching network. The hydrophone is used to detect the acoustic pressure in the field. The oscilloscope is used to detect the exciting voltage of the transducer, the output voltages of the hydrophone and the current monitor.

7.2 Alignment and positioning of the hydrophone in the field

IEC 61828:2006 is the measurement guideline of this section. Only the **geometric focal length** is used in this document.

Firstly, the exciting voltage and frequency of the transducer shall remain constant. Then, the maximum sensitivity direction of the hydrophone shall be aligned with the beam axis of the transducer to maximize the output voltage of the hydrophone. In the third step, the axial distance between the hydrophone and the transducer along the beam axis shall be adjusted to make the acoustic pulse transit time Δt_{F} between the transmitted pulse and the directly received pulse of the hydrophone equal to R/c, where R is the radius of transducer surface curvature, i.e. the **geometric focal length**, and c is the speed of sound. i.e.

$$\Delta t_{\text{F}} = R/c. \tag{2}$$

Generally, R is known by the designer or manufacturer. c is the speed of sound in water (see Annex D).

7.3 Measurements of the beamwidth and the effective half-aperture

Scanning of hydrophone along the x axis and the y axis across the **geometric focus** in the focal plane (x,y,R) allows two pairs of −3 dB and −6 dB beamwidth ($w_{3\text{x}}$, $w_{3\text{y}}$ and $w_{6\text{x}}$, $w_{6\text{y}}$) to be detected, respectively. The effective half-aperture or the effective radius of the transducer is calculated from the average beamwidths w_3 and w_6 in two directions as

$$a = \frac{\lambda R}{2\pi}\left[\frac{1{,}62}{w_3} + \frac{2{,}22}{w_6}\right] \tag{3}$$

where $w_3 = (w_{3\text{x}} + w_{3\text{y}})/2$; $w_6 = (w_{6\text{x}} + w_{6\text{y}})/2$.

7.4 Calculations of the focus half-angle and the effective area

The focus half-angle β of the spherically curved transducer is given as follows

$$\beta = \arcsin(a/R). \tag{4}$$

The **effective area** of the spherically curved transducer is given as follows:

$$A = 2\pi R^2(1 - \cos\beta) \tag{5}$$

8 Measurements of the electroacoustical parameters and the acoustic output power

8.1 Self-reciprocity method for transducer calibration

8.1.1 Experimental procedures

The transducer and the reflector are arranged in the water tank as shown in Figure F.2. The working frequency of the tone burst generator is set at a frequency f, and the output voltage is kept constant. The pulse duration is equal to or less than 30 cycles, and the duty cycle factor is approximately 1/30. The open-circuit voltage U_0 and the short-circuit current I_k of the generator are detected using the oscilloscope and the current monitor. If U_0 is very large, I_k should not be detected to avoid damage to the generator. The transducer to be measured is then excited and the position and directions of the transducer shall be adjusted precisely so that the first echo voltage U_1 is maximized when the beam axis is perpendicular to the reflector, and the reflector distance from the transducer d remains equal to the **geometric focal length** F_{geo} by keeping the pulse transit time equal to $2R/c$.

Finally, the oscilloscope and the current monitor are used to detect the exciting voltage U_T, the exciting current I_T, the phase difference θ_e between U_T and I_T, the echo voltage U_1, and the echo current I_{echo}.

If the signal-to-noise ratio of the echo current signal is too low to prevent excessive distortion, then noise reduction processing is required. The root-mean-square (RMS) echo current after noise reduction is equal to the square root of the difference between the mean square value of the detected echo current with noise and that of the detected net background noise.

8.1.2 Criterion for checking the linearity of the focused field

The reversible properties of the transducer can easily be confirmed by the designer and manufacturer based on its usage and the transfer characteristics. In the calibration procedure the ratio of the echo voltage to the exciting voltage U_1/U_{Trms} should approximately be constant to within ±5 %. The criterion for the upper limit of the linear range of the focused field is determined empirically by increasing the excitation voltage continuously and finding the point where U_1/U_{Trms} decreases down by 5 % or more. Because the acoustic pressure at the focus is much greater than that on the radiating surface, the nonlinear effects occur easier in the focal region than in the transducer itself. The upper limit of the linear working range of the transducer is generally greater than that of its linearly focused field. The nonlinear effects and the cavitation in the focused field limit the application of the self-reciprocity calibration.

8.1.3 Criterion for checking the reciprocity of the transducer

The linearity of the transducer can be checked by picking up the vibration signal U_V from a small piece of PVDF sensor glued on the radiating surface. Then, increase the exciting voltage U_T continuously and determine U_V and U_T simultaneously. The checked change value of U_V/U_T should be kept within the required tolerance, such as ±5 %, where the maximum exciting voltage represents the upper limit of the linear working range of the transducer.

A passive and **reversible transducer** working within the linear range is a **reciprocal transducer**.

8.2 Calculations of the transmitting response to current (voltage) and voltage sensitivity

According the electroacoustic reciprocity principle detailed in Annex E the **transmitting response to current (voltage)** is given by

$$S_I = \sqrt{\frac{\rho\, c\, U_1\, I_\mathrm{k}}{2\, A r_\mathrm{av}(\beta) G_\mathrm{sf} {I_\mathrm{T}}^2}}\,\mathrm{e}^{\alpha d} \tag{6}$$

$$S_U = \sqrt{\frac{\rho\, c\, U_1\, I_\mathrm{k}}{2\, A r_\mathrm{av}(\beta) G_\mathrm{sf}\, {U_\mathrm{T}}^2}}\,\mathrm{e}^{\alpha d} \tag{7}$$

and the voltage sensitivity is given by

$$M = \sqrt{\frac{2\, A\, U_1\, I_\mathrm{k}}{\rho\, c r_\mathrm{av}(\beta) G_\mathrm{sf}\, {I_\mathrm{T}}^2}}\,\mathrm{e}^{\alpha d} \tag{8}$$

where

d is the distance between the reflector and the transducer, and $d = F_\mathrm{geo}$ for a spherically curved transducer;

α is the acoustic attenuation coefficient in water (see Annex D);

$r_\mathrm{av}(\beta)$ is the **average amplitude reflection coefficient** on the reflector for the spherically curved transducer during the self-reciprocity calibration (see Annex A);

G_sf is the **diffraction correction coefficient** of the spherically curved transducer during the **free-field** self-reciprocity calibration (see Annex B and Annex C).

When the exciting voltage is very high, $U_1 I_\mathrm{k}$ should be replaced with $U_0 I_\mathrm{echo}$.

8.3 Calculations of the transmitting response at geometric focus to current (voltage)

The **transmitting response at geometric focus to current (voltage)** is given by

$$S_{I\mathrm{f}} = k_\mathrm{m} \sqrt{\frac{\rho\, c\, U_1\, I_\mathrm{k}}{2\, A r_\mathrm{av}(\beta) G_\mathrm{sf} {I_\mathrm{T}}^2}}\,\mathrm{e}^{\alpha d} \tag{9}$$

$$S_{U\mathrm{f}} = k_\mathrm{m} \sqrt{\frac{\rho\, c\, U_1\, I_\mathrm{k}}{2\, A r_\mathrm{av}(\beta) G_\mathrm{sf}\, {U_\mathrm{T}}^2}}\,\mathrm{e}^{\alpha d} \tag{10}$$

where k_m is the ratio of the acoustic pressure at the **geometric focus** to the **reference acoustic pressure** on the radiation surface of the spherically curved transducer $k_\mathrm{m} = kh = kR(1-\cos\beta)$, $k = 2\pi/\lambda$, and h is the height (depth) at the centre of the spherical segment.

8.4 Calculation of the pulse-echo sensitivity level

The **pulse-echo sensitivity** level is given by

$$L_{M\mathrm{pe}} = 20\log_{10}\left(\frac{U_1\, I_\mathrm{k}}{r_\mathrm{av}(\beta)\, U_\mathrm{T}\; I_\mathrm{T}}\right) \tag{11}$$

8.5 Measurements of the radiation conductance and the mechanical quality factor Q_m

8.5.1 Calculations of the acoustic output power and the radiation conductance

The pulse average output power for a tone burst wave equal to the temporal average output power of a continuous wave with the same acoustic pressure amplitude is given by

$$P = \frac{U_1\, I_\mathrm{k}}{4 r_\mathrm{av}(\beta) G_\mathrm{sf}} \mathrm{e}^{2\alpha d} \tag{12}$$

The **radiation conductance** is given as

$$G = \frac{U_1\, I_\mathrm{k}}{4 r_\mathrm{av}(\beta) G_\mathrm{sf}\, U_\mathrm{Trms}^2} \mathrm{e}^{2\alpha d} \tag{13}$$

8.5.2 Measurement of the frequency response of the radiation conductance

When changing working frequency adjacent to the maximum **radiation conductance** frequency f_0, the frequency response $G(f)$ of the **radiation conductance** should be measured. The resonant frequency f_0 and the edge frequencies f_1 and f_2 of the −3 dB bandwidth in the $G(f)$ curve are detected, where f_1 and f_2 are the nearest frequencies with a half-maximum **radiation conductance** values, and $f_2 > f_0 > f_1$. Then the mechanical quality factor Q_m is calculated by Formula (14), where the bandwidth is $\Delta f = f_2 - f_1$

$$Q_\mathrm{m} = f_0 / \Delta f \tag{14}$$

For transducers with low Q_m where detection of the resonant frequency f_0 is difficult, the central frequency $f_\mathrm{c} = (f_1 + f_2)/2$ should be used instead of f_0.

8.6 Measurement of the electroacoustic efficiency

8.6.1 Calculation of the electric input power

The electric input power is calculated as

$$P_\mathrm{e} = 0{,}5\; U_\mathrm{T}\; I_\mathrm{T} \cos\theta_\mathrm{e} . \tag{15}$$

8.6.2 Calculation of the electroacoustic efficiency

The **electroacoustic efficiency** is given by

$$\eta_{a/e} = P/P_\mathrm{e} \times 100\,\% . \tag{16}$$

8.7 Measurement of the electric impedance (admittance)

A network (impedance) analyzer should be used to measure the electric impedance (admittance) of the transducer in the **free-field** (in an echoless water tank) at the working frequency or within the working band.

An alternative method involves the calculation of either the electric impedance Z_T or the electric admittance Y_T, as follows

$$Z_\mathrm{T} = (U_\mathrm{T}/I_\mathrm{T})(\cos\theta_\mathrm{e} + j\sin\theta_\mathrm{e}), \tag{17}$$

$$Y_\mathrm{T} = (I_\mathrm{T}/U_\mathrm{T})(\cos\theta_\mathrm{e} - j\sin\theta_\mathrm{e}). \tag{18}$$

When the impedance is set to be in a frequency band, U_T, I_T and their phase difference θ_e in Formulas (17) and (18) should be measured over this frequency band.

9 Measurement uncertainty

Over the frequency range from 0,5 MHz to 15 MHz, five spherically curved transducers with the working frequency range 0,532 MHz to 15 MHz were measured and their values of measurement uncertainty were evaluated. The following values represent the expanded uncertainties with a coverage factor of two.

- The measurement uncertainty of the **radiation conductance** shall be better than 17 %.
- The measurement uncertainty of the acoustic output power shall be better than 17 %.
- The measurement uncertainty of the **transmitting response to voltage** shall be better than 8,5 %.
- The measurement uncertainty of the voltage sensitivity shall be better than 9 %.
- The measurement uncertainty of the **electroacoustic efficiency** shall be better than 18 %.

More information on uncertainty determination is provided in Annex H.

Annex A
(informative)

Relation of the average amplitude reflection coefficient on a plane interface of water-stainless steel and the focus half-angle for a normally incident beam of a circular spherically curved transducer [1, 2][1]

The **average amplitude reflection coefficient** is a function of the focus half-angle. On the interface its value can be calculated by Formulas (A.1) to (A.9) or by interpolation of the data in Table A.2.

The **average amplitude reflection coefficient** on the plane interface of water-stainless steel in the geometric focal plane for a spherically curved transducer is expressed by Formulas (A.1) to (A.9).

$$r_{\mathrm{av}}(\beta)=\frac{\left|\iint_A r(\theta_{\mathrm{i}})\,\mathrm{d}S\right|}{A}=\frac{\left|\int_0^{\beta} r(\theta_{\mathrm{i}})\sin\theta_{\mathrm{i}}\,\mathrm{d}\theta_{\mathrm{i}}\right|}{1-\cos\beta}, \qquad \text{(A.1)}$$

where θ_{i} is the incident angle, β is the focus half-angle, and $r(\theta_{\mathrm{i}})$ is the amplitude reflection coefficient of the plane wave with an incident angle θ_{i} on the plane reflector.

$$r(\theta_{\mathrm{i}})==\left|\frac{Z_{2\mathrm{L}}\cos^2 2\theta_{\mathrm{tT}}+Z_{2\mathrm{T}}\sin^2 2\theta_{\mathrm{tT}}-Z_{1\mathrm{L}}}{Z_{2\mathrm{L}}\cos^2 2\theta_{\mathrm{tT}}+Z_{2\mathrm{T}}\sin^2 2\theta_{\mathrm{tT}}+Z_{1\mathrm{L}}}\right|, \qquad \text{(A.2)}$$

where θ_{tL} and θ_{tT} are the refraction angles for the longitudinal wave and the transverse wave, respectively. $Z_{2\mathrm{L}}$ and $Z_{2\mathrm{T}}$ are the equivalent characteristic impedances in propagation direction of the refraction beam in the reflection medium for the longitudinal wave and the transverse wave, respectively. $Z_{1\mathrm{L}}$ is the equivalent characteristic impedance in the incident liquid medium.

$$\theta_{\mathrm{tL}}=\arcsin\left(\frac{c_{2\mathrm{L}}}{c_{1\mathrm{L}}}\sin\theta_{\mathrm{i}}\right) \qquad \text{(A.3)}$$

$$\theta_{\mathrm{tT}}=\arcsin\left(\frac{c_{2\mathrm{T}}}{c_{1\mathrm{L}}}\sin\theta_{\mathrm{i}}\right) \qquad \text{(A.4)}$$

$$Z_{2\mathrm{L}}=\rho_2\,c_{2\mathrm{L}}/\cos\theta_{\mathrm{tL}} \qquad \text{(A.5)}$$

$$Z_{2\mathrm{T}}=\rho_2\,c_{2\mathrm{T}}/\cos\theta_{\mathrm{tT}} \qquad \text{(A.6)}$$

$$Z_{1\mathrm{L}}=\rho_1\,c_{1\mathrm{L}}/\cos\theta_{\mathrm{i}} \qquad \text{(A.7)}$$

where ρ_1, $c_{1\mathrm{L}}$ and ρ_2, $c_{2\mathrm{L}}$, $c_{2\mathrm{T}}$ are the (mass) density, speed of sound in incident liquid medium and reflection medium for longitudinal wave and transverse wave, respectively.

———————

1 Numbers in square brackets refer to the Bibliography.

The critical angle on the liquid-solid interface for the longitudinal wave and transverse wave in turn are

$$\theta_{c1} = \arcsin(c_{1L}/c_{2L}) \quad \text{(A.8)}$$

and

$$\theta_{c2} = \arcsin(c_{1L}/c_{2T}) \quad \text{(A.9)}$$

Formula (A.2) is the expression of the amplitude reflection coefficient $r(\theta_i)$ for a plane wave. If the incident angle θ_i is greater than the second critical angle θ_{c2} the full inner reflection happens ($r(\theta_i)$ = 1). The parameters used in all calculations are listed in Table A.1.

Table A.1 – Parameters used in calculation of the average amplitude reflection coefficient

Medium	ρ (10^3 kg/m^3)	c_{1L} (10^3 m/s)	c_{2L} (10^3 m/s)	c_{2T} (10^3 m/s)	θ_{c1} (°)	θ_{c2} (°)
stainless steel	7,910	–	5,790	3,100	14,93	28,77
water	1	1,492	–	–	–	–

The calculated values of the amplitude reflection coefficient for different incident angles of plane wave are listed in Table A.2 and shown in Figure A.1.

Table A.2 – Amplitude reflection coefficient $r(\theta_i)$ on a plane interface of water-stainless steel for plane wave vs. the incident angle θ_i

Incident angle θ_i (°)	Reflection coefficient $r(\theta_i)$	Incident angle θ_i (°)	Reflection coefficient $r(\theta_i)$	Incident angle θ_i (°)	Reflection coefficient $r(\theta_i)$
1	0,937	16	0,913	31	1
2	0,937	17	0,901	32	1
3	0,937	18	0,904	33	1
4	0,937	19	0,909	34	1
5	0,936	20	0,913	35	1
6	0,936	21	0,916	36	1
7	0,936	22	0,918	37	1
8	0,936	23	0,919	38	1
9	0,936	24	0,919	39	1
10	0,936	25	0,919	40	1
11	0,936	26	0,920	41	1
12	0,937	27	0,923	42	1
13	0,939	28	0,934	43	1
14	0,945	29	1	44	1
15	0,991	30	1	45	1

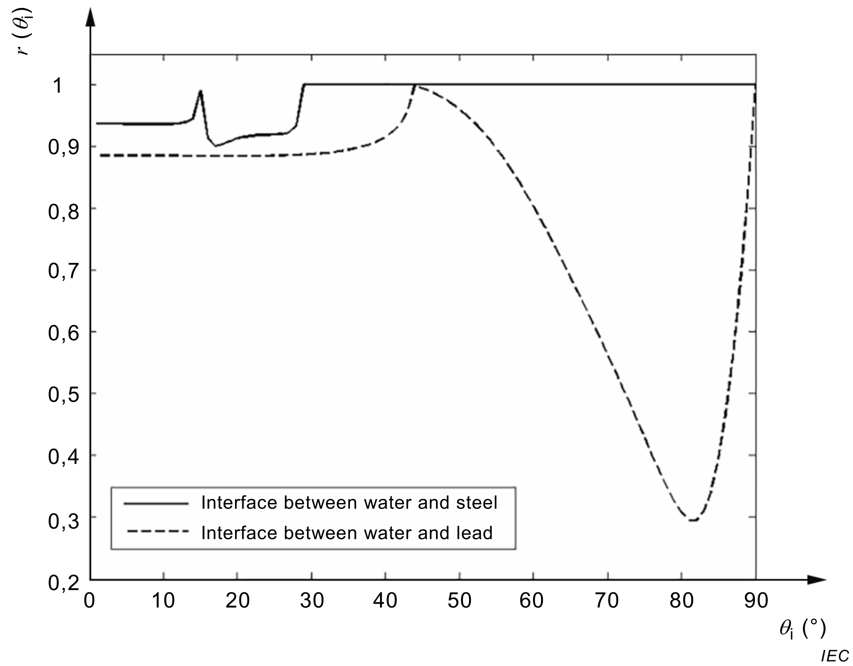

Figure A.1 – Relation curve of the amplitude reflection coefficient $r(\theta_i)$ on the interface of water-stainless steel for a plane wave with the incident angle θ_i

The values of the **average amplitude reflection coefficient** for different focus half-angles are listed in Table A.3 and shown in Figure A.2.

Table A.3 – Average amplitude reflection coefficient $r_{av}(\beta)$ on plane interface of water-stainless steel in the geometric focal plane of a spherically curved transducer vs. the focus half-angle β

Focus half-angle β (°)	Average amplitude reflection coefficient $r_{av}(\beta)$	Focus (half-)angle β (°)	Average amplitude reflection coefficient $r_{av}(\beta)$	Focus half-angle β (°)	Average amplitude reflection coefficient $r_{av}(\beta)$
1	0,937	16	0,941	31	0,695
2	0,937	17	0,936	32	0,671
3	0,937	18	0,933	33	0,589
4	0,937	19	0,930	34	0,507
5	0,937	20	0,928	35	0,429
6	0,937	21	0,927	36	0,359
7	0,937	22	0,926	37	0,293
8	0,937	23	0,926	38	0,235
9	0,937	24	0,925	39	0,185
10	0,937	25	0,925	40	0,142
11	0,937	26	0,924	41	0,111
12	0,937	27	0,924	42	0,099
13	0,937	28	0,924	43	0,106
14	0,938	29	0,894	44	0,127
15	0,940	30	0,776	45	0,154

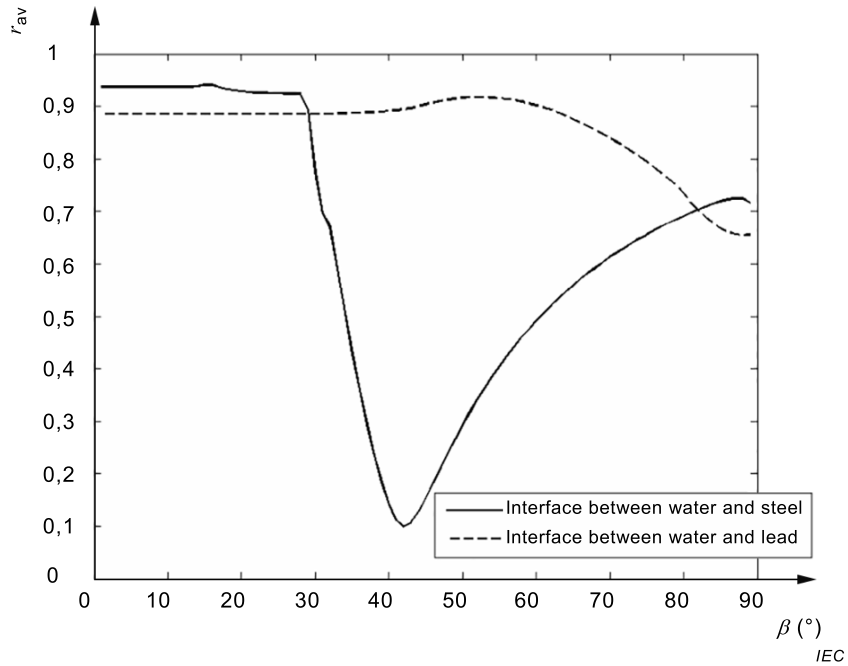

Figure A.2 – Average amplitude reflection coefficient $r_{av}(\beta)$ on the plane interface of water-stainless steel in the geometric focal plane of a spherically curved transducer vs. the focus half-angle β

Annex B
(informative)

Diffraction correction coefficient G_{sf} in the free-field self-reciprocity calibration method for circular spherically curved transducers in water neglecting attenuation [2, 3, 4]

In self-reciprocity calibration, G_{sf} $(R/\lambda,\beta)$ is the function of the ratio of the radius of curvature to the wavelength R/λ and the focus half-angle of the radiation surface of the transducer. The theoretic calculated values of G_{sf} $(R/\lambda,\beta)$ are shown in Table B.1. The calculation formula of G_{sf} is derived in Annex C. By interpolation of the data provided in Table B.1, the suitable value of G_{sf} can be obtained. The beamwidth of the main lobe (diameter of Rayleigh speckle) on the geometric focal plane of the spherically curved transducer 1,22 $R\lambda/a$ shall be smaller than the half-aperture a of the transducer (the minimum beamwidth of the circular planar piston transducer with the same half-aperture) for focusing, i.e. R < 0,81a^2/λ or β > arcsin(1,22 $\lambda/R)^{1/2}$. The Rayleigh integral is applicable for the calculation of G_{sf} for β ≤ 45°.

NOTE The values of G_{sf} in Table B.1 are with slight oscillations in both directions of R/λ and β, which leads to an uncertainty in the interpolation (see Table H.2). The empty spaces in the low focus half-angle region in the table show where the focusing condition is not satisfied. Transducers with much greater R/λ and β are limited by the effectiveness of the Rayleigh integral and by manufacture.

Table B.1 – Diffraction correction coefficients G_{sf} of a circular spherically curved transducer in the self-reciprocity calibration method [2, 3, 4]

β (°)	R/λ											
	2,68	3,35	5,04	5,36	6,70	8,04	8,40	10,1	10,7	11,8	13,4	16,1
5	–	–	–	–	–	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–	–	–
20	–	–	–	–	–	–	–	0,739	0,741	0,755	0,791	0,814
25	–	–	–	–	–	0,773	0,785	0,816	0,814	0,807	0,821	0,842
30	–	–	0,750	0,763	0,816	0,810	0,808	0,838	0,845	0,841	0,853	0,860
35	–	–	0,820	0,821	0,817	0,848	0,846	0,857	0,865	0,861	0,877	0,886
40	–	0,793	0,815	0,826	0,845	0,865	0,867	0,876	0,879	0,880	0,887	0,897
45	0,797	0,827	0,853	0,848	0,870	0,878	0,882	0,891	0,888	0,898	0,904	0,909

β (°)	R/λ											
	16,75	18,76	20,10	21,44	23,45	25,12	26,80	30,15	32,16	33,5	40,2	41,87
5	–	–	–	–	–	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	–	0,737	0,738
15	–	0,739	0,748	0,762	0,786	0,802	0,811	0,809	0,805	0,805	0,836	0,840
20	0,811	0,806	0,812	0,826	0,841	0,841	0,838	0,852	0,860	0,859	0,873	0,872
25	0,840	0,847	0,859	0,861	0,860	0,871	0,874	0,880	0,884	0,883	0,894	0,898
30	0,864	0,875	0,875	0,884	0,884	0,892	0,892	0,899	0,902	0,905	0,913	0,913
35	0,886	0,894	0,893	0,900	0,901	0,906	0,909	0,915	0,916	0,918	0,924	0,926
40	0,902	0,907	0,907	0,912	0,916	0,919	0,920	0,924	0,927	0,929	0,935	0,936
45	0,913	0,917	0,920	0,921	0,926	0,928	0,930	0,934	0,936	0,937	0,942	0,943

β (°)	R/λ											
	42,88	46,9	50,40	53,60	60,30	64,32	67,00	70,35	75,38	80,40	83,75	100,5
5	–	–	–	–	–	–	–	–	–	–	–	–
10	0,740	0,755	0,773	0,790	0,810	0,811	0,808	0,805	0,804	0,812	0,820	0,838
15	0,841	0,837	0,840	0,852	0,857	0,858	0,864	0,871	0,871	0,874	0,880	0,890
20	0,871	0,879	0,883	0,884	0,890	0,896	0,897	0,898	0,903	0,906	0,907	0,915
25	0,898	0,903	0,904	0,908	0,912	0,916	0,917	0,919	0,922	0,924	0,926	0,932
30	0,914	0,918	0,920	0,922	0,927	0,929	0,931	0,933	0,935	0,937	0,938	0,944
35	0,927	0,930	0,932	0,934	0,939	0,940	0,941	0,942	0,944	0,946	0,947	0,952
40	0,937	0,940	0,941	0,943	0,946	0,948	0,949	0,950	0,952	0,953	0,954	0,958
45	0,944	0,946	0,948	0,950	0,952	0,954	0,955	0,956	0,958	0,959	0,960	0,963

β (°)	R/λ											
	107,2	117,3	120,6	125,6	134,0	150,8	160,8	167,5	175,9	201	209,4	234,5
5	–	–	–	–	–	–	0,736	0,738	0,743	0,773	0,784	0,807
10	0,836	0,847	0,852	0,857	0,857	0,864	0,872	0,871	0,871	0,881	0,881	0,889
15	0,890	0,897	0,896	0,899	0,902	0,906	0,911	0,911	0,915	0,920	0,920	0,926
20	0,918	0,921	0,922	0,924	0,926	0,930	0,932	0,933	0,935	0,939	0,940	0,944
25	0,934	0,937	0,938	0,939	0,941	0,944	0,946	0,947	0,948	0,952	0,952	0,955
30	0,945	0,947	0,948	0,950	0,951	0,954	0,955	0,956	0,957	0,960	0,961	0,963
35	0,954	0,955	0,956	0,957	0,958	0,961	0,962	0,963	0,964	0,966	0,967	0,963
40	0,960	0,962	0,962	0,963	0,964	0,966	0,967	0,968	0,968	0,971	0,971	0,973
45	0,965	0,966	0,967	0,968	0,968	0,970	0,971	0,972	0,973	0,974	0,975	0,976

β (°)	R/λ											
	251,3	268,0	293,1	301,5	335,0	351,8	402,0	450,0	500,0	550,0	603,2	650,0
5	0,810	0,808	0,803	0,804	0,820	0,830	0,838	0,840	0,857	0,856	0,864	0,8 71
10	0,893	0,896	0,902	0,901	0,906	0,909	0,914	0,920	0,923	0,927	0,929	0,933
15	0,928	0,929	0,933	0,934	0,937	0,939	0,942	0,946	0,948	0,951	0,953	0,955
20	0,945	0,947	0,949	0,950	0,953	0,954	0,957	0,959	0,962	0,963	0,965	0,966
25	0,957	0,958	0,960	0,960	0,963	0,963	0,966	0,968	0,969	0,971	0,972	0,973

NOTE β = arcsin(a/R), $h = R$ (1 – cosβ), $\lambda = c/f$, c = 1 492 m/s in water at 23 °C, f is the frequency, and the approximation and focusing conditions are 45° ≥ β > arcsin$\left(1{,}22\lambda/R\right)^{1/2}$).

Annex C
(informative)

Calculation of the diffraction correction coefficient $G_{sf}(R/\lambda,\beta)$ in the free-field self-reciprocity calibration in a non-attenuating medium for a circular spherically curved transducer [2, 3, 4, 7]

The coordinate system with the origin point (0,0,0) at the focus of the **self-reciprocity method** for a circular spherically curved concave transducer is shown in Figure C.1 where R is the radius of curvature or the **geometrical focal length** F_{geo}, a is the half-aperture equal to $R\sin\beta$, β is the focus half-angle. A is the area of radiation surface of the concave spherical segment. Suppose there is a spherical segment area A' of the transducer's virtual image at the position of two times of the **geometric focal length** from centre of the transducer surface on the beam axis z, which is symmetrical about the geometric focal plane $(x,y,0)$ with the transducer.

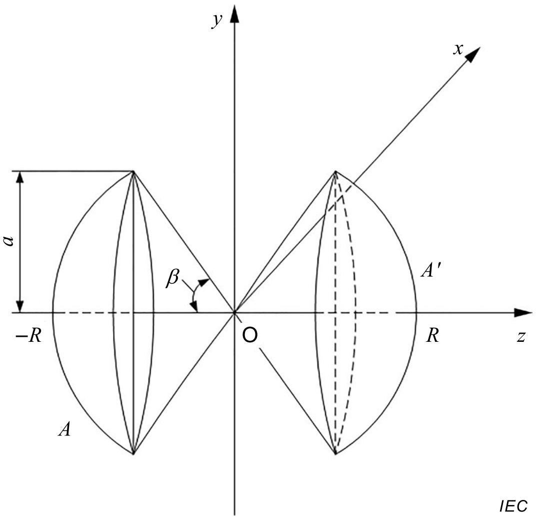

Figure C.1 – Geometry of the concave radiating surface A of a spherically curved transducer and its virtual image surface A' for their symmetry of mirror-images about the geometric focal plane $(x,y,0)$

Geometric acoustics supposes that the field is symmetrical about the geometric focal plane for mirror effect [1,18], so $A = A'$. The wave front is convergent in front of the **geometric focus** O (0,0,0) and becomes divergent beyond the focus, while it is almost a plane wave at the focus. The **average acoustic pressures** on A and A' are identical (neglecting diffraction effects in a non-attenuation medium). This is because the radius of curvature R is much greater than the wavelength and the spherical wave field is limited within the **geometric beam boundary** of two cones with the same symmetry. When accounting for the diffraction and attenuation, both **average acoustic pressures** are different and it becomes necessary to calculate the **diffraction correction coefficient** G_{sf} for the acoustic medium.

The **diffraction correction coefficient** is the ratio of the **free-field average acoustic pressure** $p_{av}(R)$ on A' to the **reference acoustic pressure** $p_0 = \rho c v_0 \approx p_{av}(-R)$ on A in a lossless medium, where v_0 is the amplitude of the uniform normal particle velocity on A, i.e.

$$G_{sf} = \left| p_{av}(R) / p_0 \right| \tag{C.1}$$

The acoustic pressure at field point $p(x,y,z)$ and the **average acoustic pressure** $p_{av}(R)$ on A' are calculated by the approximate theory of O'Neil for G_{sf} whose approximate conditions are that the depth h of the concave surface of the radiator and the wavelength λ both be small compared with the radius a; the value of h/λ is not restricted. The approximation theory is based on the Rayleigh integral. Recently, researches have shown the applicability of the Rayleigh integral and the result depends on the position in the field [6, 7, 8, 9]. These studies lead to the observation that the Rayleigh integral should be appropriate for the purposes of the present self-reciprocity calibration method if the focus half-angle β is not greater than 45° and the reflector radius is not smaller than the transducer radius.

$$p = j\frac{\rho\, c\, v_0\, \mathrm{e}^{j\omega t}}{\lambda}\iint_A \frac{\mathrm{e}^{-jk\xi}}{\xi}\mathrm{d}S = j\frac{\rho\, c v_0\, \mathrm{e}^{j\omega t}}{\lambda}\int_{-a}^{a}\int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}}\frac{\mathrm{e}^{-jk\xi}}{\xi}\frac{R}{\sqrt{R^2-x^2-y^2}}\mathrm{d}y\,\mathrm{d}x \tag{C.2}$$

$$p_{\mathrm{av}}(R) = \frac{\iint_{A'} p\,\mathrm{d}S'}{A'} = \frac{\int_{-a}^{a}\int_{-\sqrt{a^2-x'^2}}^{\sqrt{a^2-x'^2}} p\frac{R}{\sqrt{R^2-x'^2-y'^2}}\mathrm{d}y'\,\mathrm{d}x'}{A'} \tag{C.3}$$

where

ρ is the (mass) density of medium (usually water);

c is the speed of sound in medium;

v_0 is the amplitude of uniform normal particle velocity on the surface of the transducer;

λ is the wavelength;

dS is the element area on concave spherical segment A;

dS' is the element area on mirror image surface A';

$\xi = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$ is the distance between (x,y,z) on dS and (x',y',z') on dS'.

Because of the axial symmetry of the segment surface with area A and also A' about the beam axis z, Formula (C.3) can be simplified based on the spherical coordinates.

The diffraction correction coefficient becomes

$$G_{\mathrm{sf}} = \left|\frac{p_{\mathrm{av}}(R)}{p_0}\right| = \frac{(R/\lambda)^2}{1-\cos\beta}\left|\iiint\frac{\mathrm{e}^{-j\,2\pi\,\xi/\lambda}}{\xi/\lambda}\sin\theta'\,\sin\theta\,\mathrm{d}\varphi\,\mathrm{d}\theta\,\mathrm{d}\theta'\right| \tag{C.4}$$

where

$$\xi = R\sqrt{(\sin\theta\cos\varphi - \sin\theta')^2 + (\sin\theta\sin\varphi)^2 + (\cos\theta + \cos\theta')^2} \tag{C.5}$$

φ is the azimuth angle in the spherical coordinates (R,θ,φ);

θ is the polar angle in the spherical coordinates (R,θ,φ);

θ' is the polar angle in the spherical coordinates (R,θ',φ).

The integral ranges are $\varphi \in (0,2\pi)$, $\theta \in (0,\beta)$, $\theta' \in (0,\beta)$ in radians.

The element area of the divided source surface should be small enough in the integral for accuracy requirements in a way that the number of the element areas should be such that the lengths of the micro-elements $R\Delta\varphi$, $R\Delta\theta$ and $R\Delta\theta'$ are less than $\lambda/2$. It is advisable to perform a series of calculations with decreasing integration element size, to check the convergence of the results and to stop when the convergence is good enough.

A detailed list of $G_{\mathrm{sf}}(R/\lambda,\beta)$ values is given in Annex B. The needed value of G_{sf} may be obtained by interpolation of the data of Table B.1.

Annex D
(informative)

Speed of sound and attenuation in water

D.1 General

Speed of sound and acoustic attenuation coefficient in water are the main propagation parameters relevant for the methods described in this document that depend on the temperature.

D.2 Speed of sound for propagation in water

Values of speed of sound in water dependent on temperature are given in Table D.1.

Table D.1 – Dependence of speed of sound in water on temperature [5]

Temperature (°C)	Speed of sound (m/s)	Temperature (°C)	Speed of sound (m/s)	Temperature (°C)	Speed of sound (m/s)
5	1427	16	1470	27	1502
6	1431	17	1473	28	1505
7	1435	18	1476	29	1507
8	1439	19	1480	30	1509
9	1444	20	1483	31	1512
10	1448	21	1486	32	1514
11	1452	22	1489	33	1516
12	1455	23	1492	34	1518
13	1459	24	1494	35	1520
14	1463	25	1497	36	1522
15	1466	26	1500	37	1524

D.3 Acoustic attenuation coefficient for propagation in water

The value of α in the megahertz frequency range is proportional to f^2 and should be taken from the following polynomial fit as a function of temperature T (valid in the range 0 °C to 60 °C) (taken from [10], simplified):

$$\alpha/f^2 = (56{,}85 - 3{,}025\ \{T\} + 1{,}174 \times 10^{-1}\ \{T\}^2 - 2{,}954 \times 10^{-3}\ \{T\}^3 + 3{,}970 \times 10^{-5}\ \{T\}^4 - 2{,}111 \times 10^{-7}\ \{T\}^5) \times 10^{-15}\ \text{Hz}^{-2}\text{m}^{-1} \qquad \text{(D.1)}$$

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

If the amplitude attenuation coefficient in m^{-1} is to be given in dB m^{-1}, its numerical value shall be multiplied by $20\ \log_{10}(e) \approx 8{,}69$.

Annex E
(informative)

Principle of reciprocity calibration for spherically curved transducers [2, 3, 4]

E.1 Principle of reciprocity calibration for an ideal spherically focused field of a transducer

In geometric acoustics, suppose that an ideal concave spherically curved transducer excited by a current I_T transmits the sound wave in a non-attenuating medium without diffraction effects, where the normal velocity v over its radiation surface is uniform. On the other side, imagine that a point source at the **geometric focus** of the transducer transmits a divergent spherical wave whose wave front reaches and coincides with the space surface of the transducer with the same **free-field** normal velocity as if the transducer were removed. Theoretically, in ideal self-reciprocity calibration where the tone burst generator excites the transducer with pulse current amplitude I_T and an ideal plane reflector with amplitude reflection coefficient of 1 is placed on the geometric focal plane, the reflected echo field is just the field of the imagined point source. When the surface of the transducer as a receiver is blocked, the total acting force over the surface in the echo field is F and the open circuit voltage is U.

According to the **electroacoustical reciprocity principle**, Formula (E.1) is applicable [6, 19]:

$$\frac{|v|}{|I_\mathrm{T}|} == \frac{|U|}{|F|} \qquad \text{(E.1)}$$

For ideal symmetry of a spherical wave in a non-diffracting and non-attenuation field and an ideal plane reflector, the **reference acoustic pressure** on the radiating surface of the transducer $p_0 = \rho c v$ is approximately equal to the acoustic pressure amplitude averaged over the surface p_av, i.e. $p_0 \approx p_\mathrm{av}$. The **free-field** echo acoustic pressure p_2 on the former space surface of the transducer in the field of the imagining point source is also uniform and equal to $p = \rho c v = p_2$, if the transducer were removed. The output power is equal to the power through the receiving surface where the acoustic pressure and the particle velocity are in phase because the radius of curvature R is much greater than the wavelength. The scalar sum of the acting force components normal to and on the element areas over the blocked rigid surface of the transducer F is double that of the **free-field** echo acoustic pressure multiplied by the surface area A, i.e. $F = 2p_2A = 2\rho c v A$, where $A = 2\pi R^2(1 - \cos\beta)$ is the **effective area** and β is the focus half-angle.

Substitute previous relation into Formula (E.1) and consider the **free-field transmitting response to current** of the transducer $SI = p_0/I_\mathrm{T}$ and the **free-field** voltage sensitivity $M = U/p_2 = U/p = U/p_0$, so that the **reciprocity parameter** J_sf and S_I as well as the **free-field voltage sensitivity of a spherically curved transducer** can be obtained as follows:

$$J_\mathrm{sf} = \frac{M}{S_I} = \frac{U\,I_\mathrm{T}}{p^2} = \frac{F\,v}{(\rho\,c\,v)^2} = \frac{2\,A}{\rho\,c} \qquad \text{(E.2)}$$

$$S_I = \sqrt{\frac{U}{I_\mathrm{T}\,J_\mathrm{sf}}} \qquad \text{(E.3)}$$

$$M = \sqrt{\frac{U\, J_{\mathrm{sf}}}{I_{\mathrm{T}}}} \tag{E.4}$$

E.2 Principle of reciprocity calibration of a real spherically focused field of a transducer

The diffraction effect shall be taken into account in real self-reciprocity calibration. A term G_{sf} named **diffraction correction coefficient** is introduced to calculate the influence of diffraction. It is defined as the ratio of the **average acoustic pressure** $p_{2\mathrm{av}}$ on the imagined spherical segment surface area A' of the transducer's virtual image at the position of two times of the **geometric focal length** from the transducer, supposing an ideal reflection mirror on the geometric focal plane, to the **reference acoustic pressure** p_0 on transmitting surface area A of the transducer in a **free-field** of a non-attenuating medium: $G_{\mathrm{sf}} = p_{2\mathrm{av}}/p_0$, with $p_0 = \rho c v$. The geometry of the transducer surface area A and its virtual image surface area A' is shown in Figure C.1, where the radius of curvature R is equal to the **geometric focal length**. The origin of coordinates is at the **geometric focus** and xy plane is in the geometric focal plane.

The attenuation coefficient α in a medium (usually water), the diffraction in the field, and the amplitude reflection coefficient r (< 1) of a real reflector all need to be considered in the calibration simultaneously. Therefore, the real **free-field average acoustic pressure** $p'_{2\mathrm{av}}$ on the receiving spherical segment area A' drops equal to $p_0 r G_{\mathrm{sf}} \mathrm{e}^{-2\alpha d}$. Then the real open circuit voltage U' of the transducer as a receiver also drops equal to $U r G_{\mathrm{sf}} \mathrm{e}^{-2\alpha d}$ (< U) proportionally, i.e. $U = U' \mathrm{e}^{2\alpha d}/(r G_{\mathrm{sf}})$ where $d = F_{\mathrm{geo}} = R$ is the **geometric focal length**, i.e. the distance between the reflector and the transducer. From definitions $S_I = p_0/I_{\mathrm{T}}$, $M = U'/p'_{2\mathrm{av}} = U/p_0$, therefore the real **free-field reciprocity parameter** J_{sf} in the self-reciprocity calibration for a spherically curved transducer is still $2A/(\rho c)$.

E.3 Self-reciprocity calibration of a spherically curved transducer

Substituting $U = U' \mathrm{e}^{2\alpha d}/(r G_{\mathrm{sf}})$ into Formulas (E.3) and (E.4), the following formulas are derived:

$$S_I = \sqrt{\frac{U}{I_{\mathrm{T}}\, J_{\mathrm{sf}}}} = \sqrt{\frac{U'}{I_{\mathrm{T}}\, J_{\mathrm{sf}}\, r\, G_{\mathrm{sf}}}}\,\mathrm{e}^{\alpha d} \tag{E.5}$$

$$M = \sqrt{\frac{U\, J_{\mathrm{sf}}}{I_{\mathrm{T}}}} = \sqrt{\frac{U'\, J_{\mathrm{sf}}}{I_{\mathrm{T}}\, r\, G_{\mathrm{sf}}}}\,\mathrm{e}^{\alpha d} \tag{E.6}$$

The **free-field reference acoustic pressure** on the radiation surface of the transducer is

$$p_0 = S_I\, I_{\mathrm{T}} = \sqrt{\frac{U'\, I_{\mathrm{T}}\, \rho\, c}{2\, A\, r\, G_{\mathrm{sf}}}}\,\mathrm{e}^{\alpha d} \tag{E.7}$$

The **free-field transmitting voltage response** S_U is defined as the ratio of the **reference acoustic pressure** p_0 on the radiation surface of the transducer to the exciting voltage on its electric terminal:

$$S_U = \frac{1}{U_{\mathrm{T}}}\sqrt{\frac{U'\, I_{\mathrm{T}}\, \rho\, c}{2\, A\, r\, G_{\mathrm{sf}}}}\,\mathrm{e}^{\alpha d} \tag{E.8}$$

The true intensity at the **geometric focus** was derived as follows as in [7,8]:

$$I = qI_\mathrm{p} = \frac{1}{4}(1+\cos\beta)\rho c(khv)^2 \quad \text{(E.9)}$$

where $q = (1+\cos\beta)/2$ is the ratio of the true temporal-average intensity I to the derived temporal-average intensity I_p (plane-progressive-wave intensity) at the geometrical focus; $q = \rho c\mathrm{Re}(v/p) = \cos\theta_\mathrm{a}$ is also the real part of the specific acoustic admittance multiplied by the characteristic impedance ρc, and the factor $\cos\theta_\mathrm{a}$ similar to the power factor $\cos\theta_\mathrm{e}$ in electrics; θ_a is the phase difference of the particle velocity and the acoustic pressure at the **geometric focus**; $I_\mathrm{p} = \rho c(khv)^2/2$ is also the plane wave intensity; kh is the geometric focal gain; h is the depth of the spherical segment surface of transducer; k is the circular wave number; β is the focus half-angle; v is the velocity normal to and on the transducer surface; ρc is the characteristic acoustic impedance of the medium.

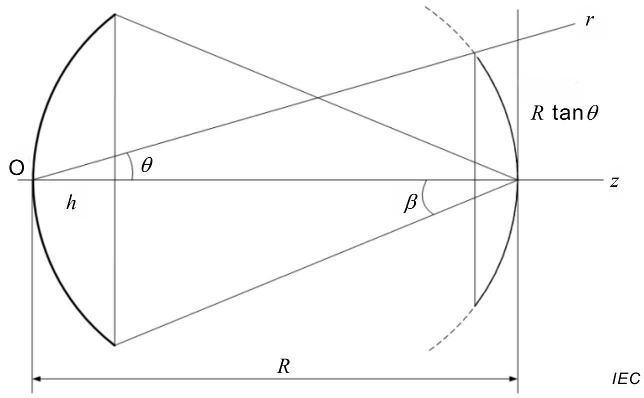

Figure E.1 – Spherical coordinates

O'Neil derived the true intensity in the r direction at points in the spherical segment surface with the constant polar angle θ and the constant radius R in the spherical coordinates (R,θ,φ), where the origin is at the centre of the transducer surface O (0,0,0) and the beam axis is the z axis, see Figure (E.1). In a certain region enclosing the central part of the geometric focal plane, his result is based on the approximation similar to the far field directivity of a flat circular piston in neglected attenuation medium [7], but he neglected q. Without neglecting these parameters, the true intensity I_R in the r direction at the points in the spherical segment surface is this result multiplied by $q\mathrm{e}^{-2\alpha R}$ as follows:

$$I_R = q\mathrm{e}^{-2\alpha R}\rho c(vkAF_0/2\pi R)^2 \quad \text{(E.10)}$$

where $F_0 = \mathrm{Jinc}(ka\sin\theta) = 2\mathrm{J}_1(ka\sin\theta)/(ka\sin\theta)$; J_1 is the Bessel function of the first kind and of the first order; q is assumed to be constant in the focal region rationally as the wave fronts near and in the geometric focal plane are approximately planar with the same phase difference θ_a and the acoustic pressure distribution $\mathrm{Jinc}(ka\sin\theta)$ [7, 9].

The power transmitted through the spherical segment surface (R,θ,φ) or a part of the geometric focal plane within a polar angle θ = constant, i.e. within a circle of radius $R\tan\theta$ in the geometric focal plane $P_\mathrm{f}(\theta)$ is

$$P_\mathrm{f}(\theta) = \int_0^\theta I_\mathrm{R}\, 2\pi R^2 \sin\theta\, \mathrm{d}\theta = \frac{1}{2}A\rho c v^2 \mathrm{e}^{-2\alpha R} G_\mathrm{fra}(\theta) \quad \text{(E.11)}$$

where

$$G_{\text{fra}}(\theta) = q(k^2 A/2\pi)\int_0^{\theta} F_0^2(ka\sin\theta)\sin\theta\,\mathrm{d}\theta = 2\int_0^{\theta}\frac{\mathrm{J}_1^2(ka\sin\theta)}{ka\sin\theta}\sec\theta\,\mathrm{d}(ka\sin\theta)$$

G_{fra} is approximately equal to the fraction of the total power transmitted through the part of the geometric focal plane within a circle of radius $R\tan\theta$.

If θ is very small and approximately equal to zero, i.e. sec $\theta \approx 1$, the following approximate formula is valid.

$$G_{\text{fra}} \approx G_{\text{a}} = 2\int_0^{\theta}\frac{\mathrm{J}_1^2(ka\sin\theta)}{ka\sin\theta}\mathrm{d}(ka\sin\theta) = 1 - \mathrm{J}_0^2(ka\sin\theta) - \mathrm{J}_1^2(ka\sin\theta) \quad \text{(E.12)}$$

where J_0 is the Bessel function of the first kind and of the zeroth order.

In fact θ is greater than zero, i.e. secθ > 1, so that $G_{\text{fra}} > G_{\text{a}}$.

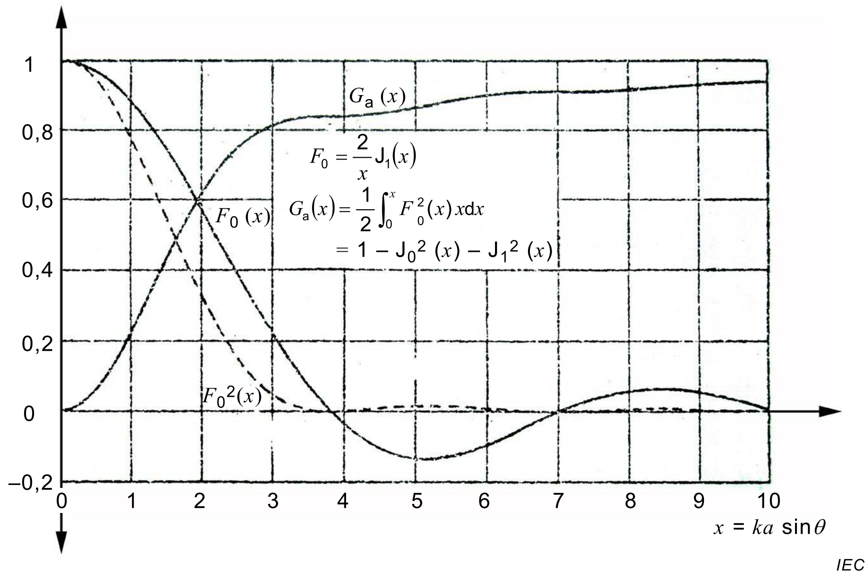

Figure E.2 Function $G_{\text{a}}(ka\sin\theta)$, diffraction pattern $F_0(ka\sin\theta)$ and $F_0^2(ka\sin\theta)$ in the geometric focal plane [7]

G_{a} is approximately equal to or less than the fraction G_{fra} of the total power transmitted through the part of the geometric focal plane within a circle of radius $R\tan\theta$ corresponding to $x = ka\sin\theta$ = constant [7]. The curve of $G_{\text{a}}(ka\sin\theta)$ function is shown in Figure E.2. The values x (= $ka\sin\theta$) relative with the typical values $G_{\text{a}}(x)$ are listed in Table E.1. For example, when G_{a} = 0,94; 0,95; 0,96; 0,97; 0,98; 0,99 in turn, correlative x = 10; 12; 15,5; 21,2; 31,4; 64,1; respectively, as shown in Table E.1.

Table E.1 – G_{a} values dependent on $ka\sin\theta$ for $\beta \leq 45°$ where $x = ka\sin\theta$ (according to O'Neil [7])

x	6	7	8	9	10	12	15,5	21,2	31,4	64,1
$G_{\text{a}}(x)$	0,90	0,91	0,92	0,93	0,94	0,95	0,96	0,97	0,98	0,99

The acoustic output power, the pulse average power of the burst wave equal to the temporal average power of the continuous wave, with the same acoustic pressure amplitude and phase difference can be calculated by integrating the true intensity over the entire semi-spherical surface of the field.

For G_{fra} = 1, $P_f = P_{fm} = A\rho c v^2 e^{-2\alpha R}$. The total acoustic output power is [11,12,13]

$$P = P_{fm} e^{2\alpha R} = \frac{p_0^2 A}{2\rho c} = \frac{U' I_T}{4 r G_{sf}} e^{2\alpha d} \quad \text{(E.13)}$$

where p_0 is the **reference acoustic pressure** $\rho c v$; $d = R$.

For the given $G_a(x)$ ≥ constant such as 0,95, 0,96, 0,97,...etc., the following inequality should be satisfied for calculating the fraction $P_{fra}(\theta)$ of the special spherically curved transducer if the Rayleigh integral is used:

$$\theta \geq \theta_{Ga} = \arcsin(x/ka) = \arcsin(x/kR\sin\beta) = \arcsin[x/(2\pi R/\lambda)\sin\beta].$$

where θ_{Ga} is the minimum upper limit of the integral in Formula E.2 for the fraction G_{fra} more than the given G_a; x is the relative variable $ka\sin\theta$ of the given G_a, see Table E.1.

This is the requirement that ensures the accuracy of the power calculation for a given $G_a(x)$ using the Rayleigh integral. Because ka of transducers is much greater than 1 in general and θ is small, the integral of G_a converges fast with increasing θ. For example, when $\theta \geq \theta_{0,95}$ = arcsin(12/ka), G_a ≥ 0,95.

Recent research has shown that the Rayleigh integral can be used in the geometric focal plane up to a limiting tanθ value that in the case of β ≤ 45° for calculation of G_{sf} is given by 1/(2sinβ) [14,15,16], i.e. when θ_{max} = arctan(1/(2sinβ)) ≥ θ_{Ga} the Rayleigh integral is applicable for calculating $P_f(\theta)$, for example θ_{max} = 35,3° for β = 45°.

Therefore, the valid conditions of Formulas (12), (13), (E.13), (E.14), (G.3) to (G.7), (G.9), (G.10) and (H.1) should be $\theta_{max} \geq \theta_{Ga}$, for the given $G_a(x)$, i.e. arctan(1/(2sinβ)) ≥ arcsin[x/(2$\pi R/\lambda$)sinβ] and β ≤ 45°.

The $(R/\lambda)_{min}$ values dependent on β within the limiting conditions $\theta_{max} \geq \theta_{Ga}$ for different given values of G_a are listed in Table E.2

Table E.2 – The $(R/\lambda)_{min}$ values dependent on β when $\theta_{max} \geq \theta_{Ga}$ and β < 45° for G_a = 0,94; 0,95; 0,96; 0,97; 0,98; 0,99

G_a \ β		β (°)								
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
G_a	**0,94**	18,5	9,70	6,92	5,64	4,93	4,50	4,22	4,03	3,90
	0,95	22,2	11,7	8,31	6,77	5,92	5,40	5,07	4,84	4,68
	0,96	28,7	15,1	10,7	8,74	7,65	6,98	6,55	6,25	6,05
	0,97	39,2	20,6	14,7	19,9	10,5	9,54	8,96	8,55	8,27
	0,98	58,1	30,6	21,7	17,7	15,5	14,1	13,3	12,7	12,2
	0,99	118,6	62,5	44,4	36,2	31,6	28,8	27,1	25,9	25,0

NOTE $(R/\lambda)_{min} = x/\{2\pi\sin\beta\cdot\sin[\arctan(1/(2\sin\beta))]\}$, $x = ka\sin\theta$ = 10; 12; 15,5; 21,2; 31,4; 64,1 in turn for G_a = 0,94; 0,95; 0,96; 0,97; 0,98; 0,99, respectively.

The G_a values should be the reference for the evaluation of measurement uncertainty of the acoustic power and the **radiation conductance**. The value of G_a can be obtained by interpolation in data of Table E.2 using the known values of β and (R/λ). The G_a value may be seen as an accuracy index of the acoustic power calculation based on Rayleigh integral. For example, for a 1,92 MHz transducer with β = 10,3° and R/λ = 51,5, so $G_a \geq 0{,}98$ can be got from Table E.2. It means that more than 98 % of the total acoustic power calculated by Formula (12) or (E.13) is within the effective applicable range of the Rayleigh integral.

The **radiation conductance** is [11,12,13]

$$G = \frac{P}{U_{\mathrm{Trms}}^2} = \frac{2\,P}{U_{\mathrm{T}}^2} = \frac{U'\,I_{\mathrm{T}}}{2\,r\,G_{\mathrm{sf}}\,U_{\mathrm{T}}^2}\,\mathrm{e}^{2\alpha d} \tag{E.14}$$

In the measurement when the incident spherically focused beam is normal to the reflector, the **average amplitude reflection coefficient** $r_{\mathrm{av}}(\beta)$ as the function of the focus half-angle should be substituted for r in the previous formulas. The value of $r_{\mathrm{av}}(\beta)$ may be picked up from Table A.2 by interpolation or calculated by Formula (A.1). Because the cable end pair of the transducer is connected with the tone burst generator to act as the electric load of the transducer when detecting the open-circuit voltage U', the real detected output echo voltage of the transducer is its cable end-loaded echo voltage U_1 rather than U', and then $U_1 = U'\,|Z_{\mathrm{i}}/(Z_{\mathrm{i}} + Z_{\mathrm{T}})|$ where Z_{i} is the inner electric impedance of the generator and Z_{T} is the electric impedance of the transducer in water. The exciting current of the generator is $I_{\mathrm{T}} = U_0/|Z_{\mathrm{i}} + Z_{\mathrm{T}}|$, and the short circuit current is $I_{\mathrm{k}} = U_0\,/|Z_{\mathrm{i}}|$, where U_0 is the open-circuit output voltage of the generator. As the detected first echo current I_{echo} is equal to $U'/|Z_{\mathrm{i}} + Z_{\mathrm{T}}|$, $U'I_{\mathrm{T}} = U_1 I_{\mathrm{k}} = U_0 I_{\mathrm{echo}}$ is valid.

In experiment, the real detectable electric parameters are U_1, I_{T}, I_{k}, U_0, U_{Trms} and I_{echo}.

$U_1 I_{\mathrm{k}}$ or $U_0 I_{\mathrm{echo}}$ should be substituted for $U'I_{\mathrm{T}}$ in the previous formulas.

Annex F
(informative)

Experimental arrangements

F.1 Experimental arrangement for determining the effective radius of a transducer [2, 3, 4, 13]

The scheme of the measurement apparatus for determining the effective half-aperture of a transducer is shown in Figure F.1.

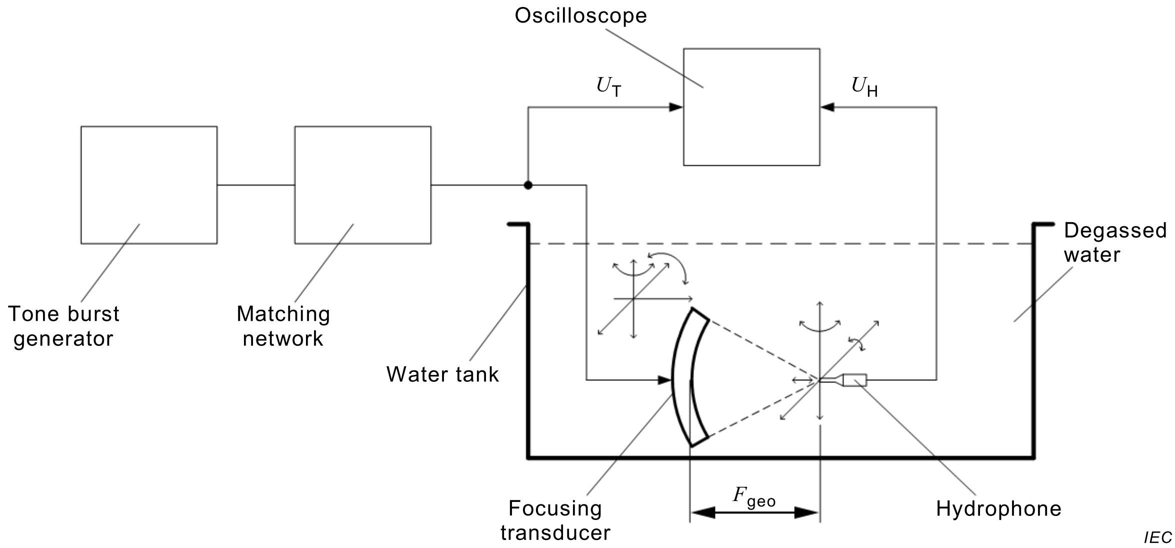

Figure F.1 – Scheme of the measurement apparatus for determining the effective half-aperture of a transducer

F.2 Experimental arrangement of the self-reciprocity calibration method for a spherically curved transducer [2, 3, 4, 13]

The scheme of **free-field self-reciprocity method** applied to a spherically curved transducer is shown in Figure F.2.

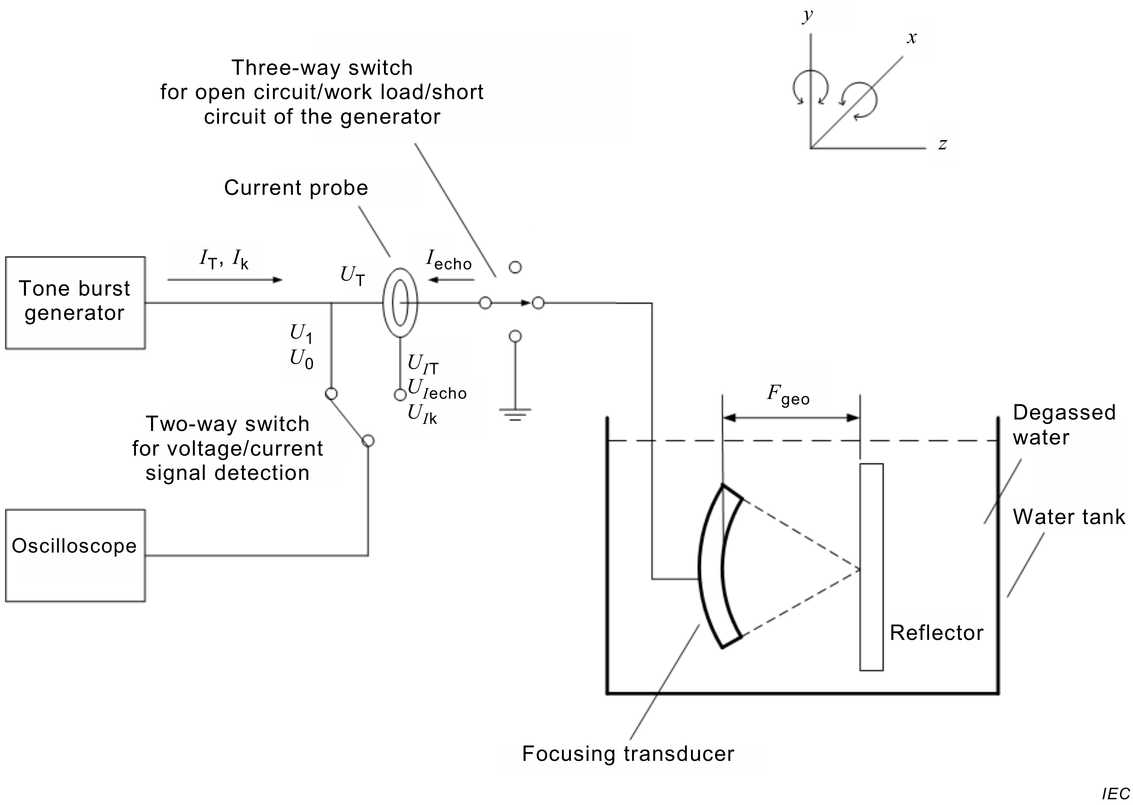

Figure F.2 – Scheme of free-field self-reciprocity method applied to a spherically curved transducer

Annex G
(informative)

Relationships between the electroacoustical parameters used in this application [13]

G.1 Relations between the free-field transmitting response to voltage (current) and the voltage sensitivity with the radiation conductance

From the definition, the **transmitting response to voltage** is given by

$$S_U = p_0 / U_\mathrm{T} = p_{0\,\mathrm{rms}} / U_{\mathrm{T\,rms}} \qquad \text{(G.1)}$$

where, p_0 and $p_{0\mathrm{rms}}$ are the **reference acoustic pressure** and the effective **reference acoustic pressure** on the radiation surface of the transducer; U_T and U_{Trms} are the exciting voltage and the exciting effective voltage of the transducer.

The **radiation conductance** of transducer is given by

$$G = P / U_{\mathrm{Trms}}^2 \,, \qquad \text{(G.2)}$$

where P is the acoustic output power of the transducer.

With the definition of acoustic output power

$$P = p_{0\mathrm{rms}}^2 \, A / (\rho\, c), \qquad \text{(G.3)}$$

the **radiation conductance** becomes

$$G = S_U^2 \, A / (\rho\, c), \qquad \text{(G.4)}$$

and

$$S_U = \sqrt{\frac{2\,G}{J_\mathrm{sf}}}\,. \qquad \text{(G.5)}$$

The **free-field transmitting response to current** of a transducer is given by

$$S_I = \sqrt{\frac{2\,G}{J_\mathrm{sf}}} \cdot \frac{U_\mathrm{T}}{I_\mathrm{T}} = S_U \, |Z_\mathrm{T}|$$

where Z_T is the electric impedance of the transducer in water.

The **free-field** voltage sensitivity of the transducer is given by

$$M = S_I \, J_\mathrm{sf} = \sqrt{2\,G\,J_\mathrm{sf}}\,|Z_\mathrm{T}| \qquad \text{(G.7)}$$

G.2 Relation of the radiation conductance and the electroacoustic efficiency

The **electroacoustic efficiency** is given as

$$\eta_{\mathrm{a/e}} = \frac{P}{P_{\mathrm{e}}} = \frac{P}{U_{\mathrm{T\,rms}}^2\, G_{\mathrm{T}}} = \frac{G}{G_{\mathrm{T}}} \tag{G.8}$$

where P_{e} is the electric input power of transducer and $G_{\mathrm{T}} = \cos\theta_{\mathrm{e}}/|Z_{\mathrm{T}}|$ is the electric input conductance with θ_{e} denoting the electric impedance phase angle of the transducer in water.

G.3 Relation of the transmitting response and voltage and acoustic output power

$$P = \frac{p_{0\,\mathrm{rms}}^2}{\rho\, c} A = \frac{\left(S_U\, U_{\mathrm{T\,rms}}\right)^2 A}{\rho\, c} \tag{G.9}$$

G.4 Relation of the pulse echo sensitivity and the radiation conductance

$$M_{\mathrm{pe}} = 2\, G\left|Z_{\mathrm{T}}\right| G_{\mathrm{sf}}\ \mathrm{e}^{-2\alpha R} \tag{G.10}$$

Annex H
(informative)

Evaluation and expression of uncertainty in the measurements of the radiation conductance

H.1 Executive standard

This document follows ISO/IEC Guide 98-3:2008 [17].

H.2 Evaluation of uncertainty in the measurement of the radiation conductance

H.2.1 Mathematical expression

The **radiation conductance** G can be calculated by

$$G = \frac{U_1 I_k}{4 r_{av}(\beta) G_{sf}(R/\lambda, \beta) U_{Trms}^2} e^{2\alpha R} \quad \text{(H.1)}$$

where

- U_1 is the voltage of the first echo from the reflector at the geometric focal plane of the spherically curved transducer;
- I_k is the short current of the generator; $r_{av}(\beta)$ is the **average amplitude reflection coefficient** of reflector in water;
- R is the radius of curvature of transducer surface;
- λ is the wavelength in water;
- β is the focus half-angle;
- G_{sf} $(R/\lambda,\beta)$ is the **diffraction corrective coefficient** in the self-reciprocity calibration for the spherically curved transducer;
- U_{Trms} is the effective value of the exciting voltage of the transducer;
- α is the attenuation coefficient in water.

The focus half-angle is given by

$$\beta = \arcsin(a/R) \quad \text{(H.2)}$$

The effective radius (effective half-aperture) is given by

$$a = \frac{\lambda F_{geo}}{2\pi}\left[\frac{1{,}62}{w_3} + \frac{2{,}22}{w_6}\right] \quad \text{(H.3)}$$

where w_3 and w_6 are the −3 dB and −6 dB beamwidths measured in the geometrical focal plane.

H.2.2 Type A evaluation of standard uncertainty

The arithmetic mean or the average value G_{av} in n times repeated measurements can be calculated by

$$G_{av} = \frac{1}{n}\sum_{i=1}^{n} G_i \,, \tag{H.4}$$

where G_i is the i-th measured value of **radiation conductance**.

The type A standard uncertainty $u_A(G_{av})$ is given by

$$u_A(G_{av}) = s_n(G_{av}) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(G_i - G_{av})^2} \,, \tag{H.5}$$

where $S_n(G_{av})$ is the positive root of the variance of the mean. To minimize $u_A(G_{av})$, n should be chosen as large as possible. However, a reasonable compromise between this recommendation and a reasonable working load may be achieved for $n \geq 6$.

H.2.3 Type B evaluation of standard uncertainty

H.2.3.1 Evaluation of standard uncertainty for different input quantities

According to the measured values of the input quantities in n times repeated measurements and the instruments used for the measurements, their combined standard uncertainties can be evaluated.

For example, the type A evaluation of standard uncertainties for the beam widths $u_A(w_3)$ and $u_A(w_6)$ can be calculated by Formula (H.5), where G was replaced with w_3 or w_6, respectively.

The type B evaluation of standard uncertainties of w_3 (or w_6) and $u_B(w_3)$ (or $u_B(w_6)$) can be determined from the resolution δ_1 (= 0,01 mm) of the displacement sensor and supposing that the length is described by a symmetric, rectangular and a priori probability distribution. Then, $u_B(w_3)$ (or $u_B(w_6)$) is set to be equal to $\delta_1/2\sqrt{3}$ (= 0,0029 mm). The type B evaluations of standard uncertainties for other input quantities are listed in Table H.1.

Then, their combined standard uncertainty can be calculated by

$$u_c(w_3) = \sqrt{u_A(w_3)^2 + u_B(w_3)^2} \text{ and } u_c(w_6) = \sqrt{u_A(w_6)^2 + u_B(w_6)^2} \,. \tag{H.6}$$

Finally, u_A, u_B and u_c; $u_A(U_1)$, $u_B(U_1)$ and $u_c(U_1)$; $u_A(U_{Trms})$, $u_B(U_{Trms})$ and $u_c(U_{Trms})$; $u_A(I_T)$, $u_B(I_T)$ and $u_c(I_T)$; $u_A(I_k)$, $u_B(I_k)$ and $u_c(I_k)$; $u_A(f)$, $u_B(f)$ and $u_c(f)$; $u_A(\alpha)$, $u_B(\alpha)$ and $u_c(\alpha)$; $u_A(\beta)$, $u_B(\beta)$ and $u_c(\beta)$ can be determined by using data in Table H.1 similarly.

Table H.1 – Type B evaluation of the standard uncertainties (SU) of input quantities in measurement

Input quantity x_i	Proposing symmetric, rectangular probability distribution, $k' = \sqrt{3}$		Relative type B evaluation of SU $u_B(x_i)/x_i$
	Resolution δ_x	$u(x) = \delta_x / 2\sqrt{3}$	
w_3, w_6 (mm)	0,01	0,002 9	0,002 9/w_{3av} 0,002 9/w_{6av}
R (mm) 23 °C	0,149 2 (transit time 0,1 μs)	0,043 3	0,043 3/R_{av}
U_1, U_{Trms} (mV)	1 (oscilloscope)	0,29	0,29/U_{1av} 0,29/U_{Trmsav}
I_T, I_k (mA)	1 (current monitor)	0,29	0,29/I_{Tav} 0,29/I_{kav}
f (MHz)	10^{-4} (oscilloscope)	$2,9 \times 10^{-5}$	$2,9 \times 10^{-5}/f_{av}$
θ_e (°)	0,1 (oscilloscope)	0,029	0,029/θ_{eav}
c (mm/μs)	0,001 4 (temperature change: 0,5 °C)	$4,1 \times 10^{-4}$	$4,1 \times 10^{-4}/c$ 0,027 % (23 °C)
α/f^2 ($MHz^{-2}cm^{-1}$) 23 °C	$0,025 \times 10^{-4}$ (temperature change: 0,5 °C)	$7,3 \times 10^{-7}$	$7,3 \times 10^{-7}/(\alpha/f^2)$ 0,31 % (23 °C)

The type B variance of effective radius is

$$u_B^2(a) = \sum_{i=1}^{4} c_i^2 u^2(x_i) = \sum_{i=1}^{4} \left(\frac{\partial a}{\partial x_i} \right)^2 u^2(x_i) \qquad \text{(H.7)}$$

where x_i (i = 1, 2, 3, 4) represent R, λ, w_3, w_6. and c_i denote the corresponding sensitivity coefficients.

According to Formula (H.3), the following sensitive coefficients can be derived:

$$c_1(a) = \frac{\partial a}{\partial R} = \frac{a}{R}$$

$$c_2(a) = \frac{\partial a}{\partial \lambda} = \frac{a}{\lambda}$$

$$c_3(a) = \frac{\partial a}{\partial w_3} = -\frac{a}{w_3(1+\frac{2,22\, w_3}{1,62\, w_3})} \approx -\frac{a}{2w_3}$$

$$c_4(a) = \frac{\partial a}{\partial w_6} = -\frac{a}{w_6(1+\frac{2,22\, w_6}{1,62\, w_6})} \approx -\frac{a}{2w_6}$$

Combining (H.3) and (H.7), one can get

$$u_{\mathrm{B}}(a)/a = \left[\frac{1}{R^2}u^2(R) + \frac{1}{\lambda^2}u^2(\lambda) + \frac{1}{4w_3^2}u^2(w_3) + \frac{1}{4w_6^2}u^2(w_6)\right]^{1/2} \tag{H.8}$$

$$u_{\mathrm{c}}(a)/a = \sqrt{[u_{\mathrm{A}}(a)/a]^2 + [u_{\mathrm{B}}(a)/a]^2} \tag{H.9}$$

where $u_{\mathrm{c}}(a)$ is the combined standard uncertainty of the effective radius.

H.2.3.2 Evaluation of standard uncertainty for the focus half-angle of a focusing transducer

From Formula (H.2), the following sensitive coefficients can be derived:

$$c_1(\beta) = \frac{\partial\beta}{\partial a} = -\frac{2}{R\sqrt{1-\left(\frac{a}{R}\right)^2}} = -2\tan\beta/a$$

$$c_2(\beta) = \frac{\partial\beta}{\partial R} = -\frac{2a}{R^2\sqrt{1-\left(\frac{a}{R}\right)^2}} = -2\sin\beta\tan\beta/R$$

The type B standard uncertainty of the focus half-angle is given by

$$u_{\mathrm{B}}(\beta) = \sqrt{c_1^2(\beta)u^2(a) + c_2^2(\beta)u^2(R)}$$

$$= \sqrt{(2\tan\beta\cdot u(a)/a)^2 + (2\sin\beta\tan\beta\cdot u(R)/R)^2} \tag{H.10}$$

The combined standard uncertainty of the focus half-angle is given by

$$u_{\mathrm{c}}(\beta)/\beta = \sqrt{[u_{\mathrm{A}}(\beta)/\beta]^2 + [u_{\mathrm{B}}(\beta)/\beta]^2} \tag{H.11}$$

H.2.4 Evaluation of the combined standard uncertainty for the radiation conductance

H.2.4.1 Type B evaluation of the standard uncertainty for the radiation conductance

H.2.4.1.1 Type B_1 component

From Formula (H.1), the following sensitive coefficients can be derived:

$$c_1(G) = \frac{\partial G}{\partial U_1} = \frac{G}{U_1},$$

$$c_2(G) = \frac{\partial G}{\partial I_k} = \frac{G}{I_k},$$

$$c_3(G) = \frac{\partial G}{\partial \beta} = -\left[\frac{1}{r_{\text{av}}}\left(\frac{\partial r_{\text{av}}}{\partial \beta}\right) + \frac{1}{G_{\text{sf}}}\left(\frac{\partial G_{\text{sf}}}{\partial \beta}\right)\right]G\,,$$

$$c_4(G) = \frac{\partial G}{\partial R} = \left[2a - \frac{1}{G_{\text{sf}}}\left(\frac{\partial G_{\text{sf}}}{\partial R}\right)\right]G$$

$$c_5(G) = \frac{\partial G}{\partial U_{\text{Trms}}} = -\frac{2G}{U_{\text{Trms}}}\,,$$

$$c_6(G) = \frac{\partial G}{\partial \alpha} = 2RG$$

where $\left(\frac{\partial r_{\text{av}}}{\partial \beta}\right)$, $\left(\frac{\partial G_{\text{sf}}}{\partial \beta}\right)$ and $\left(\frac{\partial G_{\text{sf}}}{\partial R}\right)$ are obtained by interpolating from the data in Table A.2 and Table B.1, respectively. For U_1, I_{k} and U_{Trms} the average values measured can be used.

Because the echo voltage U_1 and the short current I_{k} are dependent on the exciting voltage U_{Trms}, the following correlation coefficients should be calculated:

$$r(U_1, U_{\text{Trms}}) = \frac{\sum_{i=1}^{n}(U_{1,i} - U_{1,\text{av}})(U_{\text{Trms},i} - U_{\text{Trms,av}})}{(n-1)s(U_1)s(U_{\text{Trms}})}$$

$$r(I_{\text{k}}, U_{\text{Trms}}) = \frac{\sum_{i=1}^{n}(I_{\text{k},i} - I_{\text{k,av}})(U_{\text{Trms},i} - U_{\text{Trms,av}})}{(n-1)s(I_{\text{k}})s(U_{\text{Trms}})}$$

where $(U_{1,i} - U_{1,\text{av}})$, $(I_{\text{k},i} - I_{\text{k,av}})$, $(U_{\text{Trms},i} - U_{\text{Trms,av}})$, $s(I_{\text{k}})$ and $s(U_{\text{Trms}})$ are calculated from the data of n times repeated measurements of the **radiation conductance**, where $s(x_i)$ = $(n)^{1/2}s_n(x_i)$.

The covariance term in the type B_1 component of the standard uncertainty is

$$\begin{aligned} &2\sum_{i=1}^{4}\sum_{j=i+1}^{5}\frac{\partial G}{\partial x_i}\frac{\partial G}{\partial x_j}r(x_i,x_j)u(x_i)u(x_j) \\ &= 2\left[\frac{\partial G}{\partial U_1}\frac{\partial G}{\partial U_{\text{Trms}}}r(U_1,U_{\text{Trms}})u(U_1)u(U_{\text{Trms}}) + \frac{\partial G}{\partial I_{\text{k}}}\frac{\partial G}{\partial U_{\text{Trms}}}r(I_{\text{k}},U_{\text{Trms}})u(I_{\text{k}})u(U_{\text{Trms}})\right] \end{aligned} \quad \text{(H.12)}$$

$$u_{\text{B1}}(G) = \sqrt{\sum_{i=1}^{6}\left(\frac{\partial G}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{4}\sum_{j=i+1}^{5}\frac{\partial G}{\partial x_i}\frac{\partial G}{\partial x_j}\cdot r(x_i,x_j)u(x_i)u(x_j)} \quad \text{(H.13)}$$

where $u_{\text{B1}}(G)$ is the square root of the variance of the type B_1 evaluation of the standard uncertainty, which is calculated according to ISO/IEC Guide 98-3.

H.2.4.1.2 Type B other components and Type A of uncertainty

Type B and Type A components and typical data of the relative uncertainties are shown in Table H.2

Table H.2 – Components of the standard uncertainty for the measurement of the radiation conductance using the self-reciprocity method

No.	Source of the uncertainty component	Symbol	Relative uncertainty $u_{Bi}(G)/G$ or $u_A(G_{av})/G_{av}$
1	Type B evaluation of standard uncertainty by calculation from experimental data	u_{B1}	< 1,0 %
2	Introduced by aligning the beamwidth the direction of the hydrophone and scanning in measurements of the effective radius (half-)angle	u_{B2}	1,7 %
3	Introduced by calculation of the diffraction correction coefficient G_{sf} in Table B.1	u_{B3}	1,4 %
4	Read out the G_{sf} value in Table B.1 by interpolation	u_{B4}	1,2 %
5	Introduced by calculation of $r_{av}(\beta)$ value in Table A.2	u_{B5}	1,2 %
6	Introduced by adjusting the beam direction and position of the transducer	u_{B6}	1,4 %
7	Low ratio of signal to noise in measurement of current	u_{B7}	1,2 %
8	Calculated G_{sf} and the acoustic output power based on Rayleigh integral different to their true values, where the focus half-angle is not greater than 45°	u_{B8}	7,0 %
9	Type A evaluation of standard uncertainty of measurement for G	$u_A(G_{av})$	< 3,5 %

NOTE Data given in Table H.2 are evaluated from experiments using seven transducers as a reference. These transducers were used with frequencies of 0,53 MHz, 1,52 MHz, 1,92 MHz, 5 MHz, 5,27 MHz, 10 MHz, and 15 MHz, respectively. The results of five transducers are shown in Table H.3.

H.2.4.2 Combined standard uncertainty

The combined standard uncertainty is given by

$$u_C(G_{av}) = \sqrt{{u_A}^2(G_{av}) + \sum_{i=1}^{8} u_{Bi}^2(G)} \qquad \text{(H.14)}$$

H.2.4.3 Expanded uncertainty

For the coverage factor k = 2 the expanded uncertainty is

$$U = 2u_C(G) \qquad \text{(H.15)}$$

Five spherically curved transducers were measured and evaluated for the measurement uncertainty. Table H.3 lists the results of these measurements and evaluation of uncertainty.

Table.H.3 – The measurement results and evaluated data of uncertainty for five transducers

No.	*f* (MHz)	*R* (mm)	*β* (°)	*a/λ*	*G* (mS)	*Ga* (< G_{fra})	*q*	*U(a)/a* %	*u(β)/β* %	*uB1/G* %	*uA/G* %	*uC/G* %	*U* %
1	0,532	30	19,6	3,60	3,30	0,96	0,971	0,444	1,74	0,250	1,69	7,89	15,8
2	1,92	40	10,3	22,3	5,23	0,98	0,992	0,720	0,644	0,253	2,33	8,05	16,1
3	5,0	50	10,8	32,1	0,173	0,99	0,991	1,42	1,70	0,353	1,18	7,80	15,6
4	10,1	25	8,8	25,7	15,1	0,99	0,994	3,13	2,76	0,774	0,241	7,74	15,5
5	15,0	60	5,5	57,3	3,05	0,99	0,998	1,25	1,13	0,412	0,988	7,77	15,5

Bibliography

[1] DU, G. H., ZHU, Z. M., GONG, X. F., *Fundamentals of Acoustics* (in Chinese, third Edition), Chapter 11, Section 11.2.3, pp. 529-531, Nanjing University Press, 2013, Nanjing, Jiangsu, China

[2] SHOU, W. D., YU, L. L., DUAN, S. M., ZHU, H. Q., YANG, P., HU, J. M., BU, S. Z., HU, B., Research on electro-acoustic characteristics and measurements of spherically focusing transducer (in Chinese), *Technical Acoustics* 32, 379-388 (2013)

[3] SHOU, W. D., YAN, J. Y., WANG, H. Z., QIAN, D. C., Free-field reciprocity calibration in a convergent spherical acoustic wave of a focusing transducer, *Chin. Phys. Lett.* 19, 1131-1136 (2002)

[4] SHOU, W. D., DUAN, S. M., HE, P. Z., XIA, R. M., QIAN, D. C., Calibration of a focusing transducer and miniature hydrophone as well as acoustic power measurement based on free-field reciprocity in a spherically focused wave field, *IEEE Trans. UFFC* 53, 564-570 (2006)

[5] WANG, R. J. et al., *Handbook of Underwater Materials* (in Chinese), Chapter 8, pp.114-115, Science Press, 1982, Beijing, China

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

[7] O'NEIL, H. T., Theory of focusing radiator, *J. Acoust.Soc. Am.* 21, 516-526 (1949)

[8] BEISSNER, K., Some basic relations for ultrasonic fields from circular transducers with a central hole, *J. Acoust. Soc. Am.* 131(1), 620-627 (2012)

[9] XU, Z., CHEN, H., QIAN, M., CHENG, Q., Visualization of point-focusing ultrasonic field by three-dimensional schlieren method (in Chinese), *Technical Acoustics* 33 (2), 202-204 (2014)

[10] PINKERTON, J. M. M., The absorption of ultrasonic waves in liquids and its relation to molecular constitution, *Proc. Phys. Soc. B* 62, 129-141 (1949)

[11] DUAN, S. M., SHOU, W. D., HE, P. Z., A novel method to measure acoustic power of focusing transducer with spherical surface on self-reciprocity theorem, *Chin. Phys. Lett.* 22, 146-149 (2005)

[12] SHOU, W. D., YU, L. L., YANG, P., BU, S. Z., HU, B., Self-reciprocity calibration method of ultrasonic transducer as well as its application in power measurement and relation with radiation force balance method, *Technical Acoustics* 33, 446-453 (2014)

[13] GB/T32522-2016, *Acoustics-Electroacoustic characteristics and measurements of piezoelectric spherically focusing ultrasonic transducers* (in Chinese)

[14] CATHIGNOL, D., SAPOZHNIKOV, O. A., On the application of the Rayleigh integral to the calculation of the field of a concave focusing radiator, *Acoust. Phys.* 45 (6), 735-742 (1999)

[15] SAPOZHNIKOV, O. A., SINILO, T. V., Acoustic field produced by a concave radiating surface with allowance for the diffraction, *Acoust. Phys.* 48 (6), 720-727 (2002)

[16] BEISSNER, K., On the lateral resolution of focused ultrasonic fields from spherically curved transducers, *J. Acoust. Soc. Am.* 134 (5), 3943-3947 (2013)

[17] ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to expression of uncertainty in measurement (GUM:1995)*

[18] IEC 61828:2006, *Ultrasonics – Focusing transducers – Definitions and measurement methods for the transmitted fields*

[19] IEC 62127-2:2007, *Ultrasonics – Hydrophones – Part 2: Calibration for ultrasonic fields up to 40 MHz*
IEC 62127-2:2007/AMD1:2013

[20] IEC 60565:2006, *Underwater acoustics – Hydrophones – Calibration in the frequency range 0,01 Hz to 1 MHz*

[21] IEC 61161, *Ultrasonics – Power measurement – Radiation force balances and performance requirements*

____

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch