BS EN 61094-3:2016

Incorporating corrigendum December 2016

BSI Standards Publication

Electroacoustics — Measurement microphones

Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique (IEC 61094-3:2016)

bsi.

National foreword

This British Standard is the UK implementation of EN 61094-3:2016. It is identical to IEC 61094-3:2016, incorporating corrigendum December 2016. It supersedes BS EN 61094-3:1996 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee EPL/29, Electroacoustics.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Published by BSI Standards Limited 2017

ISBN 978 0 580 97575 2
ICS 17.140.50; 33.160.50

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2016.

Amendments/corrigenda issued since publication

Date	Text affected
28 February 2017	Implementation of IEC corrigendum December 2016: subclause 5.7.2 corrected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 61094-3

September 2016

ICS 17.140.50; 33.160.50

Supersedes EN 61094-3:1995

English Version

Electroacoustics - Measurement microphones - Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique (IEC 61094-3:2016)

Électroacoustique - Microphones de mesure - Partie 3: Méthode primaire pour l'étalonnage en champ libre des microphones étalons de laboratoire par la méthode de réciprocité
(IEC 61094-3:2016)

Messmikrofone - Teil 3: Primärverfahren zur Freifeld-Kalibrierung von Laboratoriums-Normalmikrofonen nach der Reziprozitätsmethode
(IEC 61094-3:2016)

This European Standard was approved by CENELEC on 2016-07-19. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

European foreword

The text of document 29/873/CDV, future edition 2 of IEC 61094-3, prepared by IEC TC 29, Electroacoustics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61094-3:2016.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2017-04-19
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2019-07-19

This document supersedes EN 61094-3:1995.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 61094-3:2016 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61094-8:2012 NOTE Harmonized as EN 61094-8:2012.

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

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

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 61094-1	2000	Measurement microphones -- Part 1: Specifications for laboratory standard microphones	EN 61094-1	2000
IEC 61094-2	2009	Electroacoustics - Measurement microphones -- Part 2: Primary method for the pressure calibration of laboratory standard microphones by the reciprocity technique	EN 61094-2	2009
ISO 9613-1	-	Acoustics; attenuation of sound during propagation outdoors; part_1: calculation of the absorption of sound by the atmosphere	-	-
IEC/TS 61094-7	-	Measurement microphones -- Part 7: Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones	-	-
ISO/IEC Guide 98-3	-	Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)	-	-

This page deliberately left blank

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROACOUSTICS – MEASUREMENT MICROPHONES –

Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique

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.

International Standard IEC 61094-3 has been prepared by IEC technical committee 29: Electroacoustics.

This second edition cancels and replaces the first edition published in 1995. This edition constitutes a technical revision.

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

a) a new informative annex describing the use of time-selective techniques to minimize the influence of acoustic reflections from the measurement setup;
b) provision for the calibration of microphones in driven shield configuration.

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

CDV	Report on voting
29/873/CDV	29/892A/RVC

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

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

A list of all parts in the IEC 61094 series, published under the general title *Electroacoustics – Measurement microphones*, can be found on the IEC website.

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

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

ELECTROACOUSTICS – MEASUREMENT MICROPHONES –

Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique

1 Scope

This part of IEC 61094

- specifies a primary method of determining the complex free-field sensitivity of laboratory standard microphones so as to establish a reproducible and accurate basis for the measurement of sound pressure under free-field conditions,
- is applicable to laboratory standard microphones meeting the requirements of IEC 61094-1,
- is intended for use by laboratories with highly experienced staff and specialized equipment.

NOTE The calibration principle described in this part of IEC 61094 is also applicable to working standard microphones, preferably used without their protection grid.

2 Normative references

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

IEC 61094-1:2000, *Measurement microphones – Part 1: Specifications for laboratory standard microphones*

IEC 61094-2:2009, *Electroacoustics – Measurement microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique*

IEC TS 61094-7:2006, *Measurement microphones – Part 7: Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones*

ISO 9613-1, *Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61094-1, IEC 61094-2, ISO/IEC Guide 98-3 and the following apply.

3.1
phase
<free-field sensitivity of a microphone> phase angle between the open-circuit voltage and the sound pressure that would exist at the position of the acoustic centre of the microphone in the absence of the microphone, for a sinusoidal plane progressive wave of given frequency and direction of sound incidence, and for given environmental conditions

Note 1 to entry: Phase is expressed in degrees (°) or radians (rad).

3.2
acoustic centre
<microphone> point from which approximately spherical wavefronts from a sound-emitting transducer producing a sinusoidal signal at a given frequency appear to diverge with respect to a small region around an observation point at a specified direction and distance from the sound source

Note 1 to entry: The acoustic centre of a reciprocal transducer when used as a receiver is coincident with the acoustic centre when used as a transmitter.

Note 2 to entry: This definition only applies to regions of the sound field where spherical or approximately spherical wavefronts are observed.

3.3
equivalent point-transducer
notional transducer occupying a single point that, when located at the position of its acoustic centre, simulates the transmitting or receiving characteristics of a microphone, for a sinusoidal signal of given frequency, and for a given observation direction and distance

3.4
principal axis
<microphone> line through the centre of and perpendicular to the diaphragm of the microphone

3.5
free-field conditions
airborne sound-field environment where sound waves can propagate freely without disturbances of any kind

4 Reference environmental conditions

The reference environmental conditions are:

- temperature 23,0 °C
- static pressure 101,325 kPa
- relative humidity 50 %

5 Principles of free-field calibration by reciprocity

5.1 General principles

5.1.1 General

A reciprocity calibration of microphones may be carried out by means of three microphones, two of which shall be reciprocal, or by means of an auxiliary sound source and two microphones, one of which shall be reciprocal.

NOTE 1 If one of the microphones is not reciprocal it can only be used as a sound receiver.

NOTE 2 Laboratory standard microphones are reciprocal when used within their linear operating range.

5.1.2 General principles using three microphones

Let two of the microphones be coupled acoustically under free-field conditions. Using one of them as a sound source and the other as a sound receiver, the electrical transfer impedance is measured. When the acoustic transfer impedance of the system is known, the product of the free-field sensitivities of the two coupled microphones can be determined. Using pair-wise combinations of three microphones, three such mutually independent sensitivity products are available, from which an expression for the free-field sensitivity of each of the three microphones can be derived.

5.1.3 General principles using two microphones and an auxiliary sound source

First, let the two microphones be coupled acoustically under free-field conditions, and the product of the free-field sensitivities of the two microphones be determined as described in 5.1.2. Next, let the two microphones be sequentially presented to the same sound pressure, set up by the auxiliary sound source under identical free-field conditions. The ratio of the two output voltages will then equal the ratio of the free-field sensitivities of the two microphones. Thus, from the product and the ratio of the free-field sensitivities of the two microphones, an expression for the free-field sensitivity of each of the two microphones can be derived.

NOTE In order to obtain the ratio of free-field sensitivities, a direct comparison method can be used, and the auxiliary sound source can be another type of transducer or a third microphone having mechanical or acoustical characteristics which differ from those of the microphones being calibrated.

5.2 Basic expressions

Laboratory standard microphones are considered reciprocal and thus the two-port formulae of the microphones can be written as:

$$\begin{aligned} \underline{z}_{11}\,\underline{i} + \underline{z}_{12}\,\underline{q} &= \underline{U} \\ \underline{z}_{21}\,\underline{i} + \underline{z}_{22}\,\underline{q} &= \underline{p} \end{aligned} \tag{1}$$

where

$\underline{p}$	is the sound pressure, at the acoustical terminals of the microphone, in pascals (Pa);
$\underline{U}$	is the signal voltage at the electrical terminals of the microphone, in volts (V);
$\underline{q}$	is the volume velocity through the acoustical terminals (diaphragm) of the microphone, in cubic metres per second (m^3/s);
$\underline{i}$	is the current through the electrical terminals of the microphone, in amperes (A);
$\underline{z}_{11} = \underline{Z}_e$	is the electrical impedance of the microphone when the diaphragm is blocked, in ohms (Ω);
$\underline{z}_{22} = \underline{Z}_a$	is the acoustic impedance of the microphone when the electrical terminals are unloaded, in pascal-seconds per cubic metre ($Pa \cdot s \cdot m^{-3}$),
$\underline{z}_{12} = \underline{z}_{21} = \underline{M}_p\,\underline{Z}_a$	is equal to the reverse and forward transfer impedances in volt-seconds per cubic metre ($V \cdot s \cdot m^{-3}$), M_p being the pressure sensitivity of the microphone in volts per pascal ($V \cdot Pa^{-1}$).

NOTE Underlined symbols represent complex quantities.

Formula (1) may then be rewritten as:

$$\begin{aligned} \underline{Z}_e\,\underline{i} + \underline{M}_p\,\underline{Z}_a\,\underline{q} &= \underline{U} \\ \underline{M}_p\,\underline{Z}_a\,\underline{i} + \underline{Z}_a\,\underline{q} &= \underline{p} \end{aligned} \tag{2}$$

which constitute the formulae of reciprocity for the microphone.

When the sound pressure $\underline{p}$ is not uniform over the surface of the diaphragm, as will be the case at high frequencies when the microphone is located in a plane progressive wave, the location of the acoustic terminals is given through the equivalent point-transducer simulating the microphone. In this case, Formula (1) will also be valid for the real microphone through a special interpretation of $\underline{\boldsymbol{p}}$, see 5.4 and 5.5.

5.3 Insert voltage technique

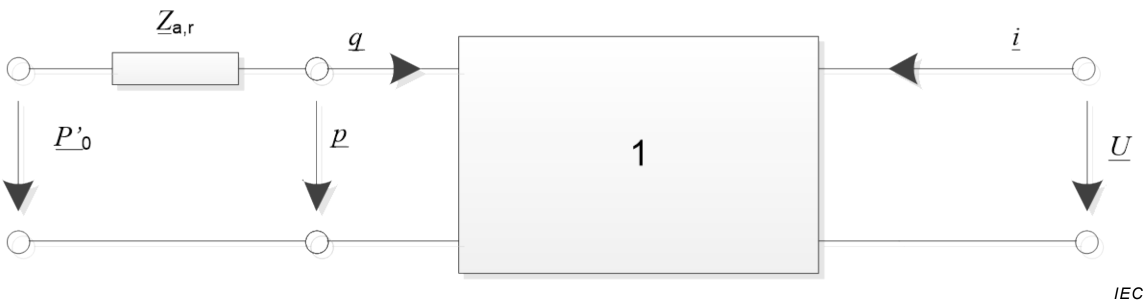
The insert voltage technique is used to determine the open-circuit voltage of a microphone when it is electrically loaded.

Let a microphone having a certain open-circuit voltage and internal electrical impedance be connected to an external electrical load impedance. To measure the open-circuit voltage, an impedance, small compared to the load impedance, is connected in series with the microphone and a calibrating voltage applied across it.

Let a sound pressure and a calibrating voltage of the same frequency be applied alternately. When the calibrating voltage is adjusted until it gives the same voltage drop across the load impedance as results from the sound pressure on the microphone, the open-circuit voltage will be equal in magnitude to the calibrating voltage.

5.4 Free-field receiving characteristics of a microphone

Let a microphone be placed in a progressive plane wave of sound pressure p_0. The equivalent circuit of the microphone is given in Figure 1, where $\underline{\boldsymbol{p}}'_{\mathbf{0}}$ is the sound pressure when the diaphragm is blocked and $\underline{\boldsymbol{p}}$ the actual sound pressure at the acoustic terminals of the microphone. $\underline{Z}_{\mathrm{a,r}}$ is the acoustic radiation impedance of the microphone.



Key

1 microphone

Figure 1 – Equivalent circuit for a receiving microphone under free-field conditions

Let $\underline{\boldsymbol{p}}'_{\mathbf{0}}$ be related to $\underline{\boldsymbol{p}}_{\mathbf{0}}$ through:

$$\frac{\underline{\boldsymbol{p}}'_{\mathbf{0}}}{\underline{\boldsymbol{p}}_{\mathbf{0}}} = \underline{S}(f,\theta)$$

where $\underline{S}(f,\theta)$ is the scattering factor and depends on the geometrical configuration of the microphone. It is a function of frequency f and angle of incidence θ of the sound wave impinging on the diaphragm of the microphone.

As $\underline{\boldsymbol{p}} = \underline{\boldsymbol{p}}'_{\mathbf{0}} - \underline{Z}_{\mathbf{a,r}}\underline{\boldsymbol{q}}$, the two-port Formulae (2) can be written as:

$$\underline{U} = \underline{Z}_{\mathbf{e}}\underline{i} + \underline{M}_{\mathrm{p}}\underline{Z}_{\mathbf{a}}\underline{q}$$
$$\underline{p}'_{\mathbf{0}} = \underline{M}_{\mathrm{p}}\underline{Z}_{\mathbf{a}}\underline{i} + (\underline{Z}_{\mathbf{a}} + \underline{Z}_{\mathbf{a,r}})\underline{q} \tag{3}$$

and thus, from the basic definition, the free-field sensitivity is given by:

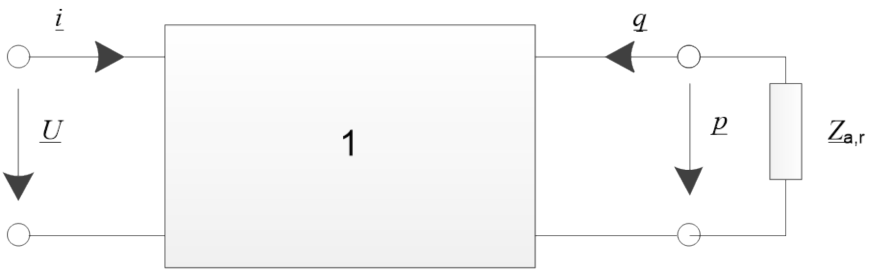
$$\underline{M}_{\mathrm{f}} = \left(\frac{\underline{U}}{\underline{p}_{\mathbf{0}}}\right)_{i=0} = \underline{M}_{\mathrm{p}}\frac{\underline{Z}_{\mathbf{a}}}{\underline{Z}_{\mathbf{a}} + \underline{Z}_{\mathbf{a,r}}}\underline{S}(f,\theta) \tag{4}$$

Formula (4) shows that the difference between the pressure sensitivity and the free-field sensitivity is determined not only by the geometry of the microphone through the scattering factor $\underline{S}(f,\theta)$ but also by the relation between the acoustic impedance of the microphone and the radiation impedance.

NOTE The effect of the microphone venting mechanism is not accounted for in the model presented and will also influence the difference between the pressure sensitivity and free-field sensitivity at low frequencies (see 6.1).

5.5 Free-field transmitting characteristics of a microphone

Let a microphone be used as a transmitter under free-field conditions. The equivalent circuit of the microphone is given in Figure 2.



Key

1 microphone

Figure 2 – Equivalent circuit for a transmitting microphone under free-field conditions

As $\underline{p} = -\underline{Z}_{\mathrm{a,r}}\underline{q}$, the two-port formulae of transmitting microphone can be written as:

$$\underline{U} = \underline{Z}_{\mathbf{e}}\,\underline{i} + \underline{M}_{\mathrm{p}}\,\underline{Z}_{\mathbf{a}}\,\underline{q}$$
$$0 = \underline{M}_{\mathrm{p}}\,\underline{Z}_{\mathbf{a}}\,\underline{i} + (\underline{Z}_{\mathbf{a}} + \underline{Z}_{\mathbf{a,r}})\,\underline{q} \tag{5}$$

so that:

$$-\underline{q} = \frac{\underline{M}_{\mathrm{p}}\underline{Z}_{\mathbf{a}}}{\underline{Z}_{\mathbf{a}} + \underline{Z}_{\mathbf{a,r}}}\underline{i} = \frac{\underline{M}_{\mathrm{f}}}{\underline{S}(f,\theta)}\underline{i}$$

From the general principle of reciprocity, it can be deduced that at a remote point, the equivalent point-transducer will act as a simple source of strength $-\underline{q}\ \underline{S}(f,\theta) = \underline{M}_{\mathrm{f}}\ \underline{i}$ and the sound pressure $\underline{p}_{\mathbf{0}}$ at the distance d between this point and the equivalent point-transducer will then be:

$$\underline{p}_0 = \mathrm{j}\frac{\rho f}{2d}\underline{M}_\mathrm{f}\ \underline{i}\ \mathrm{e}^{-\underline{\gamma} d}\ \mathrm{e}^{\mathrm{j}\omega t} = \mathrm{j}\frac{\rho f}{2d}\underline{M}_\mathrm{f}\ \underline{i}\ \mathrm{e}^{\mathrm{j}(\omega t - kd)}\ \mathrm{e}^{-\alpha d} \tag{6}$$

where

$\underline{\gamma} = \alpha + \mathrm{j}k$ is the complex propagation coefficient, α is the air attenuation coefficient, k is the wave number and ρ is the density of the gas.

NOTE Derivation of Formula (6) given above is based on a lumped parameter representation of the microphone (see Formula (1)). A more rigorous derivation can be obtained by using an integral form of representation of the formulae of the microphone.

5.6 Reciprocity procedure

Let two microphones denoted as microphone 1 and microphone 2 with free-field sensitivities $\underline{M}_{\mathrm{f},1}$ and $\underline{M}_{\mathrm{f},2}$, respectively, be situated in a free field facing each other and with coincident principal axes. A current $\underline{i}_1$ through the electrical terminals of microphone 1 will produce a sound pressure $\underline{p}_0$ given by Formula (6) at a distance d from its acoustic centre, under free-field conditions. When introducing microphone 2 into the sound field, neglecting losses in the medium and assuming no interaction takes place between the two microphones, the open-circuit voltage of microphone 2 will be:

$$\underline{U}_2 = \underline{M}_{\mathrm{f},2}\,\underline{p}_0 = \mathrm{j}\frac{\rho f}{2d_{12}}\underline{M}_{\mathrm{f},1}\underline{M}_{\mathrm{f},2}\,\underline{i}_1\,\mathrm{e}^{\mathrm{j}(\omega t - kd_{12})}$$

d_{12} being the distance between the acoustic centres of microphone 1 and microphone 2.

At high frequencies the molecular relaxation effects and viscous losses in air cannot be neglected and thus, the product of the free-field sensitivities is given by:

$$\underline{M}_{\mathrm{f},1}\underline{M}_{\mathrm{f},2} = -\mathrm{j}\frac{2d_{12}}{\rho f}\frac{\underline{U}_2}{\underline{i}_1}\ \mathrm{e}^{\mathrm{j}kd_{12}}\ \mathrm{e}^{\alpha d_{\mathrm{m}12}}, \tag{7}$$

where $d_{\mathrm{m}12}$ is the physical distance between the diaphragms of microphone 1 and microphone 2, being the actual distance the sound wave has propagated.

5.7 Final expressions for the free-field sensitivity

5.7.1 Method using three microphones

Implementing the principles in 5.1.2, let the electrical transfer impedance $\underline{U}_2/\underline{i}_1$ be denoted by $\underline{Z}_{\mathrm{e},12}$ with similar expressions for microphone pairs involving the third microphone, microphone 3. The final expression for the complex free-field sensitivity of microphone 1 is then:

$$\underline{M}_{\mathrm{f},1} = \left(\frac{2}{\rho f}\frac{d_{12}d_{31}}{d_{23}}\frac{\underline{Z}_{\mathrm{e},12}\ \underline{Z}_{\mathrm{e},31}}{\underline{Z}_{\mathrm{e},23}}\mathrm{e}^{\mathrm{j}k(d_{12}+d_{31}-d_{23})}\ \mathrm{e}^{\alpha(d_{\mathrm{m}12}+d_{\mathrm{m}31}-d_{\mathrm{m}23})}\right)^{1/2} \tag{8}$$

Similar expressions apply for microphone 2 and microphone 3.

The modulus and phase of the free-field sensitivity can be derived from Formula (8), whereupon the phase should be referred to the full four-quadrant phase range, i.e. 0 to 2π rad or 0 to 360°.

5.7.2 Method using two microphones and an auxiliary sound source

If only two microphones and an auxiliary sound source are used, then implementing the principles in 5.1.3, the final expression for the complex free-field sensitivity is:

$$\underline{M}_{\mathrm{f},1} = \left(\underline{r}_{12} \frac{2d_{12}}{\rho f} \underline{Z}_{\mathrm{e},12} \, \mathrm{e}^{\mathrm{j}kd_{12}} \, \mathrm{e}^{\alpha d_{\mathrm{m}12}} \right)^{1/2} \tag{9}$$

where the ratio of the free-field sensitivities of the two microphones, $\underline{r}_{12}$, is measured by comparison against the auxiliary source, see 5.1.3.

6 Factors influencing the free-field sensitivity

6.1 General

The free-field sensitivity of a laboratory standard microphone depends on polarizing voltage, as it has an electrostatic transductions mechanism, and the environmental conditions.

The basic mode of operation of a polarized electrostatic microphone assumes that the electrical charge on the microphone is kept constant at all frequencies. This condition cannot be maintained at very low frequencies and the product of the microphone capacitance and the polarizing resistance determines the time constant for the flow of charge to and from the microphone. While the open-circuit sensitivity of the microphone, as obtained using the insert voltage technique, will be determined correctly, the absolute output from an associated preamplifier to the microphone will decrease at low frequencies in accordance with this time constant.

The construction principles of laboratory standard microphones imply that the static pressure behind and in front of the diaphragm shall remain the same. To comply with this a pressure equalizing tube is used to connect the back cavity of the microphone to the external medium. The effect of this tube is that the free-field sensitivity will approach zero at very low frequencies (below a few hertz). The technique described in this standard is not suitable for determining the free-field sensitivity in this frequency range.

Furthermore, the definition of the free-field sensitivity implies that certain requirements be fulfilled by the measurements. It is essential during a calibration that these conditions are controlled sufficiently well so that the resulting uncertainty components are small.

6.2 Polarizing voltage

The sensitivity of a laboratory standard microphone is approximately proportional to the polarizing voltage and thus the polarizing voltage actually used during the calibration shall be reported.

To comply with IEC 61094-1, a polarizing voltage of 200,0 V is recommended.

6.3 Shield configuration

The open-circuit voltage, and therefore the free-field sensitivity, depends on the shield configuration. Consequently, IEC 61094-1 specifies a reference mechanical configuration for the shield for use in determining the open-circuit voltage. While the reference mechanical configuration is essential, the shield can either be grounded (grounded-shield configuration), or the output voltage from the microphone can be applied to the shield (driven-shield configuration). It shall be stated whether the driven-shield or grounded-shield configuration was used in the measurements.

The same shield configuration shall apply to both transmitter and receiver microphones during the calibration.

If any non-standard configuration is used, the results of a calibration shall be referred to the reference mechanical configuration.

If the manufacturer specifies a maximum mechanical force to be applied to the central electrical contact of the microphone, this limit shall not be exceeded.

NOTE 1 When the shield is driven, the loading impedance as seen from the microphone is maximized, and it can be described more accurately than in the case of using the grounded shield configuration. In the ideal case, in which the microphone is a perfectly linear and passive device and the shield is either grounded, or driven from a zero source impedance, there is no difference between the open-circuit sensitivity with grounded or driven shield.

NOTE 2 In the driven-shield configuration, applying the output voltage from the microphone to the shield means that any difference between the signal applied on the shield and on the centre-pin of the microphone is negligible.

NOTE 3 If a microphone is connected to a preamplifier by means of an adapter there is the possibility that the open-circuit voltage of the microphone is not determined properly by the insert voltage technique at high frequencies. The deviations depend on the load impedance as seen from the microphone.

6.4 Acoustic conditions

The free-field sensitivity of a microphone depends on the geometrical configuration of the housing containing the preamplifier. For this reason, the microphone and the shield configuration shall be attached to a cylinder whose diameter is equal to the nominal diameter of the microphone, see Table 1 and Table 2 in IEC 61094-1:2000. The length of the cylinder shall be long compared to the diameter of the microphone. A minimum length of twenty times the diameter of the microphone with a gradually tapered transition to the supporting structure is recommended. This arrangement shall also apply to the transmitter microphone.

The definition of the free-field sensitivity of a microphone refers to the sound pressure in an undisturbed plane progressive wave. In the far field of a sound source located under free-field conditions, spherical waves are encountered which, at a sufficient distance from the source, are approximately plane waves in a limited region. Thus, the distance between the receiver microphone and the transmitter microphone shall be great enough to ensure approximately plane waves in a suitable region around the receiver microphone (see 7.3). Conversely, the influence of reflections from the interior surfaces of an anechoic chamber usually increases as the distance between the two microphones is increased. Also the scattering factor $\underline{S}(f,\theta)$ depends on the character of the sound field and can only be unambiguously defined for a true plane progressive wave. Therefore, the metrological conditions should be carefully chosen and it may be preferable to carry out calibrations at more than one distance to assess the calibration uncertainty attributable to dependence on these conditions.

6.5 Position of the acoustic centre of a microphone

The position of the acoustic centre of a microphone can be determined from measurements of the sound pressure produced by the microphone when used as a sound source in a free field, as a function of distance r from an arbitrarily chosen reference point of the microphone. In a limited region of the far field, the sound pressure, corrected for the effect of sound attenuation, will follow the $1/r$-law, r being referred now to the acoustic centre of the microphone. Thus, when plotting the inverse value of the measured sound pressure as a function of the distance from an arbitrarily chosen reference point of the microphone (most conveniently the centre of the diaphragm), a straight line can be fitted (e.g. by the methods of least squares) through the plotted values. The intersection of this straight line and the abscissa axis determines the position of the acoustic centre relative to the reference point.

The acoustic centres used to determine d_{12} (see 5.7) shall relate to the orientation and separation used during the free-field calibrations.

Annex A contains information on typical values for the position of the acoustic centre for laboratory standard microphones.

NOTE Specific applications may require defining the acoustic centre of the microphone at a fixed position, for instance, at the centre of the microphone diaphragm. Whereas this would result in the modulus of the sensitivity having a dependence on the distance between microphone and source, it may provide a useful reference for the phase response. While using this fixed acoustic centre in the calculations is possible, an alternative is to determine the sensitivity using the acoustic centre based on the inverse-distance law and later apply a correction to the phase response to the preferred position of the acoustic centre.

6.6 Dependence on environmental conditions

6.6.1 General

The general dependence of the pressure sensitivity on environmental conditions is given in 6.5 of IEC 61094-2:2009. In addition to this, the free-field sensitivity further depends on environmental conditions through the relation given in Formula (4). In this formula, the radiation impedance is a function of the air density and speed of sound. Similarly the scattering factor $\underline{S}(f,\theta)$ depends on the wavelength and thus on the speed of sound in air.

6.6.2 Static pressure

In addition to the dependence described in IEC 61094-2:2009 (6.5 and Annex D), a further dependence is caused by the relationship between the acoustic impedance of the microphone and its radiation impedance due to the change in the density of air with static pressure. The major influence of the mass term of the radiation impedance is to lower the resonance frequency of the microphone slightly.

6.6.3 Temperature

In addition to the dependence described in IEC 61094-2:2009 (6.5 and Annex D), a further dependence is caused by the relationship between the acoustic impedance of the microphone and its radiation impedance due to the change in the density and the speed of sound in air with temperature. In addition, a dependence is caused by the scattering factor $\underline{S}(f,\theta)$ according to Formula (4) due to the change in the speed of sound in air with temperature. IEC TS 61094-7:2006, Clause 6 describes the temperature dependence of the difference between the free-field sensitivity and the pressure sensitivity that shall be considered in addition to the temperature dependence of the pressure sensitivity itself.

NOTE If a microphone is exposed to excessive temperature variations, a permanent change in sensitivity can result.

6.6.4 Humidity

According to Formula (4) a slight effect may be found on the free-field sensitivity in addition to influence on the pressure sensitivity, caused by the influence of humidity on the density and speed of sound in air.

NOTE Certain conditions can influence the stability of polarizing voltage and backplate charge and therefore influence the sensitivity. For example the surface resistance of the insulation material between the backplate and the housing of the microphone can deteriorate under excessively humid conditions, particularly if the material is contaminated. The surface resistance has a noticeable effect on the sensitivity of the microphone at low frequencies, especially on the phase response.

6.6.5 Transformation to reference environmental conditions

When reporting the results of a calibration, the free-field sensitivity should be referred to the reference environmental conditions if reliable correction data are available. For moderate deviations from reference environmental conditions, the corrections used for the pressure sensitivity may be applied with appropriately increased uncertainty.

The actual conditions during the calibration should be reported.

NOTE During a calibration, the temperature of the microphone can be different from the ambient air temperature.

6.7 Considerations concerning measurement space

The test space shall be as free as possible of any effects that cause instabilities in the sound field, for example between measurements of microphone combinations. These include changing environment conditions, air flows, thermal gradients and electromagnetic disturbance.

It shall have a level of background noise and vibration that enables the measurements to meet the signal-to-noise requirements of the measurement system used. In practice, steps should be taken to reduce the background noise as much as possible.

7 Calibration uncertainty components

7.1 General

In addition to the factors mentioned in Clause 6, which affect the free-field sensitivity, further uncertainty components are introduced by the method, the equipment and the degree of care under which the calibration is carried out. Factors which affect the calibration in a known way shall be measured or calculated with as high accuracy as practicable in order to minimize their influence on the resulting uncertainty.

7.2 Electrical transfer impedance

Various methods are used for measuring the electrical transfer impedance with the necessary accuracy, and no preference is given.

The current through the transmitter is usually determined by measuring the voltage across a calibrated impedance in series with the transmitter microphone. To ensure a correct determination of the current, the grounded or driven shield configuration shall be attached to the transmitter microphone. The calibration of the series impedance shall include any cable capacitance and other load impedance present when measuring the voltage across the impedance. This allows the electrical transfer impedance to be determined from a voltage ratio measurement and the calibrated value of series impedance.

The voltage used to excite the transmitter microphone shall be such that the uncertainty arising from harmonics, either from this source or generated by the microphone, is small compared to the random uncertainty.

Noise or other interference such as cross-talk, whether of acoustical or other origin, shall not unduly affect the determination of the free-field sensitivity.

The presence of electrical cross-talk results in apparent deviations from the $1/r$-law having a periodicity of one wavelength.

NOTE 1 Frequency selective techniques can be used to improve the signal-to-noise ratio.

NOTE 2 Time selective techniques can be used to minimize the influence of cross-talk and reflections from the environment and the mechanical supports in the calibration set-up. See Annex D.

NOTE 3 Cross-talk can be measured with the microphones positioned as during a calibration, but with the receiver microphone substituted by a dummy microphone having the same capacitance and external geometry as the receiver microphone, and then determining the resulting difference in the electric transfer impedance. Alternatively, cross-talk can be determined by setting the polarizing voltage to zero during a calibration. In both methods, frequency selective techniques are advantageous.

7.3 Deviations from ideal free-field conditions

During a calibration, certain acoustic requirements shall be fulfilled (see 6.4). The calibration shall be carried out in a free field. This condition is most practically obtained in an anechoic room where wind is absent and airborne noise is minimal. Due to the non-ideal performance of the absorption material lining the walls and the finite size of the room, some frequency dependent reflections from the walls will occur and result in deviations from the $1/r$-law for the modulus of sound pressure. The magnitude of these deviations will depend on the distance and direction from the sound source. At a given frequency, the deviations as a function of distance will show a periodicity between a half and one wavelength, corresponding to a reflected wave that is parallel or perpendicular to the direct wave. Normally, the smallest deviations are obtained in a region around the centre of the room and where the principle axis is neither parallel nor perpendicular to any walls of the room. However, the presence of braces, grillwork, cables, supports of various kinds, lighting, ventilation, etc., may give rise to disturbances in the sound field.

The influence of these disturbing reflections can be reduced to acceptable levels only by exercising the utmost care when establishing the calibration system and procedure.

Annex D gives examples of time selective techniques that may also be used to reduce the influence of deviations from ideal free-field conditions.

Further, in order to ensure an approximately plane wave in a suitable region around the receiving microphone, it is recommended that the distance between the two microphones during the calibration should be greater than ten times the nominal diameter of the microphones.

7.4 Attenuation of sound in air

Under practical conditions, sound waves propagating in a free field will be attenuated due to molecular relaxation effects and to thermal-viscous losses.

This attenuation depends on the frequency of the sound, the water vapour content and the temperature of the air. It is determined by the real part α, the air attenuation coefficient, of the complex propagation coefficient $\underline{\gamma}$ in Formula (6).

Values of the air attenuation coefficient expressed in nepers per metre shall be calculated from the formulae given in Annex B.

7.5 Polarizing voltage

In order to determine the polarizing voltage, provision can be made for measuring this voltage directly at the terminals of the microphone. This is important when the polarizing voltage is obtained from a high-impedance source, due to the finite insulation resistance of the microphone. Alternatively, the insulation resistance of the microphone can be measured and verified to be sufficiently high that a measurement of the polarizing voltage supply with the microphone removed, or a measurement at a low impedance port of the polarizing voltage supply, are valid.

7.6 Physical properties of air

Certain quantities describing the physical properties of air are required for calculating the sensitivity of a microphone or its dependence on environmental conditions. These quantities depend on environmental conditions such as static pressure, temperature and humidity. Values of the quantities and their dependencies on environmental conditions are described in Annex B and in IEC 61094-2:2009, Annex F.

7.7 Imperfection of theory

The practical implementation of the reciprocity theorem and the derivation of the acoustic transfer impedance are based on some idealized assumptions about the microphones and the movement of the microphone diaphragm. The following are examples where these assumptions may not be fully valid.

- Small scale imperfections in the microphones may lead to different movement patterns of the diaphragm between individual samples of a given microphone model, resulting in variations in the position of the acoustic centre, in particular at high frequencies.
- Microphones may not be reciprocal. The effect of this can be minimized by combining only microphones of the same model.

7.8 Uncertainty on free-field sensitivity level

The uncertainty on the free-field sensitivity level should be determined in accordance with ISO/IEC Guide 98-3. When reporting the results of a calibration, the uncertainty, as a function of frequency, shall be stated as the expanded uncertainty of measurement using a coverage factor k corresponding to a 95 % confidence probability.

Due to the complexity of the final expression for the free-field sensitivity in Formula (8), the uncertainty analysis of the acoustic transfer impedance is usually performed by repeating a calculation while the various components are changed one at a time by their associated uncertainty. The difference from the result derived by the unchanged components is then used to determine the standard uncertainty related to the various components.

Table 1 lists a number of components affecting the uncertainty of a calibration. Not all of the components may be relevant in a given calibration setup because various methods are used for measuring the electrical transfer impedance, for minimizing the influence of correlated reflections from the environment and for determining the acoustic centres of the microphones.

Table 1 – Uncertainty components

Measured quantity	Relevant subclause no.
Electrical transfer impedance	
Series impedance	7.2
Voltage ratio	7.2
Cross-talk	7.2
Inherent and ambient noise	7.2
Distortion	7.2
Reflections from surroundings	7.2; 7.3
Frequency	7.2
Receiver shield	6.3
Transmitter shield	6.3; 7.2
Acoustic transfer impedance	
Distance	6.4; 6.5
Static pressure	6.6.2; 7.6
Temperature	6.6.3; 7.6
Relative humidity	6.6.4; 7.6
Standing waves between microphones	7.3
Air attenuation	7.4; Annex B
Microphone parameters	
Acoustic centres	6.5
Polarizing voltage	6.2; 7.5
Imperfection of theory	
Deviation from plane-waves	6.4; 7.3
Processing of results	
Mathematical manipulations	

Measured quantity	Relevant subclause no.
Rounding error	
Repeatability of measurements	
Static pressure corrections	6.6; Annex C
Temperature corrections	6.6; Annex C

The uncertainty components listed in Table 1 are generally a function of frequency and shall be derived as a standard uncertainty. The uncertainty components should be expressed in a linear form but a logarithmic form is also acceptable as the values are typically very small and the derived final expanded uncertainty of measurement is then essentially the same.

Annex A
(informative)

Values for the position of the acoustic centre

As defined, the acoustic centre depends on orientation, on frequency and on the distance of the observation point from the microphone. At sufficiently remote observation points, the effect of the acoustic centre position on the calibration uncertainty diminishes. At such distances, the centre of the diaphragm may be taken as the acoustic centre. For distances in the range 150 mm to 500 mm, normally used when carrying out reciprocity calibrations, the values given in the bibliography and shown in Figure A.1 may be applied. The values for the position of the acoustic centre refers to the principal axis and are given relative to the surface of the diaphragm as a function of frequency for microphones type LS1P and LS2aP. A positive sign indicates that the acoustic centre is in front of the diaphragm. The uncertainty of the values in Figure A.1 is estimated to be less than 2 mm below the resonance frequency of the microphones. At present such data are not available for other types of microphones.

NOTE In general, the acoustic centre will be different for individual microphones of the same type, particularly at high frequencies around and above the resonance frequency of the microphone. In practice, use of an average or typical value of the acoustic centre may simplify the calculation of the free-field sensitivity. In this case it is necessary to add an additional uncertainty component associated with the variability of the acoustic centre to the uncertainty budget.

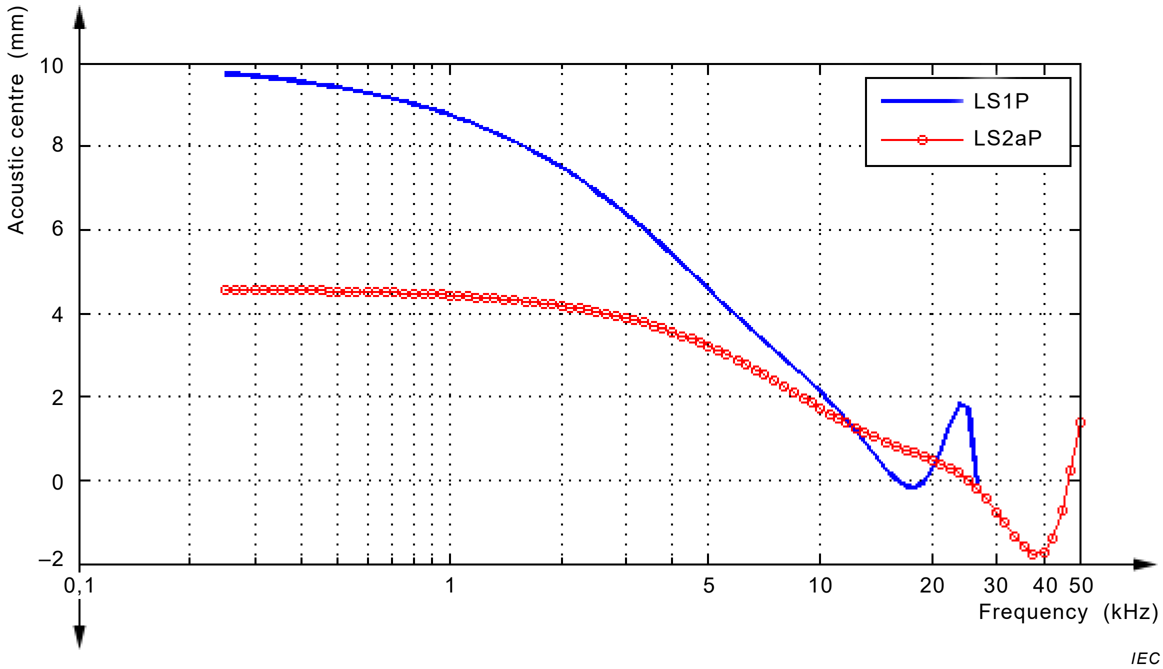


Figure A.1 – Example of the estimated values of the acoustic centres of LS1P and LS2aP microphones given in the bibliographical references for Annex A

Annex B
(normative)

Values of the air attenuation coefficient

B.1 General

Certain quantities, describing the properties of air, enter the expressions for calculating the free-field sensitivity of the microphones, see Formulae (6) and (7). Methods for calculating the density and speed of sound in humid air (including dispersion effects) are described in IEC 61094-2. Methods for calculating the air attenuation coefficient are given in ISO 9613-1. Its Annex A describes the physical mechanisms for the phenomenon, and 5.2 and Annex B give formulae for calculating the attenuation coefficient as a function of frequency, temperature, static pressure and relative humidity. The calculation procedure in B.2 follows the guidelines in ISO 9613-1 with a few adjustments to comply with the procedures given in IEC 61094-2.

B.2 Calculation procedure

The formulae given in this annex are based on the measured environmental variables:

t temperature, in degree Celsius (°C);

p_s static pressure, in pascals (Pa);

H relative humidity, as a percentage (%).

The calculation of the air absorption takes into account that the humid air is not an ideal gas and thus some additional quantities and constants are used:

T = 273,15 + t, the thermodynamic temperature, in kelvin (K);

T_{20} = 293,15 K (20 °C);

$p_{s,r}$ = 101 325 Pa;

c speed of sound at actual environmental conditions, in metres per second (m/s);

$p_{sv}(t)$ saturation water vapour pressure, in pascals (Pa);

x_w molar fraction of water vapour in air;

α_{cl} classical absorption neglecting the influence of molecular relaxation processes;

α_{rot} absorption caused by rotational molecular relaxation processes, in nepers per metre (Np/m);

$\alpha_{vib,O}$ molecular absorption due to vibrational relaxation of oxygen, in nepers per metre (Np/m);

$\alpha_{vib,N}$ molecular absorption due to vibrational relaxation of nitrogen, in nepers per metre (Np/m);

f_{rO} oxygen relaxation frequency, in hertz (Hz);

f_{rN} nitrogen relaxation frequency, in hertz (Hz);

α = $\alpha_{cl} + \alpha_{rot} + \alpha_{vib,O} + \alpha_{vib,N}$ air attenuation coefficient, in nepers per metre (Np/m).

Step 1

Determine the saturation water vapour pressure (see also IEC 61094-2:2009, F.2):

$$p_{sv}(t) = \exp(1{,}237\,884\,7 \cdot 10^{-5} \cdot T^2 - 1{,}912\,131\,6 \cdot 10^{-2} \cdot T + 33{,}937\,110\,47 - 6{,}3343\,184\,5 \cdot 10^3 \cdot T^{-1})$$

Step 2

Determine the molar fraction of water vapour:

$$x_\mathrm{w} = \frac{H}{100}\left(\frac{p_\mathrm{sv}}{p_\mathrm{s}}\right)\left(1{,}000\,62 + 3{,}14\cdot 10^{-8}\cdot p_\mathrm{s} + 5{,}6\cdot 10^{-7}\cdot t^2\right)$$

Step 3

Determine the relaxation frequencies:

$$f_\mathrm{rO} = \left(\frac{p_\mathrm{s}}{p_\mathrm{s,r}}\right)\left[24 + 4{,}04\cdot 10^6\, x_\mathrm{w}\left(\frac{0{,}2 + 10^3\, x_\mathrm{w}}{3{,}91 + 10^3\, x_\mathrm{w}}\right)\right]$$

$$f_\mathrm{rN} = \left(\frac{p_\mathrm{s}}{p_\mathrm{s,r}}\right)\left(\frac{T}{T_{20}}\right)^{-\frac{1}{2}}\left[9 + 28\cdot 10^3\, x_\mathrm{w}\exp\left(-4{,}170\left(\left(\frac{T}{T_{20}}\right)^{-\frac{1}{3}} - 1\right)\right)\right]$$

Step 4

Determine the individual absorption components:

$$\alpha_\mathrm{cl} + \alpha_\mathrm{rot} = 18{,}42\times 10^{-12}\, f^2\left(\frac{p_\mathrm{s}}{p_\mathrm{s,r}}\right)^{-1}\left(\frac{T}{T_{20}}\right)^{\frac{1}{2}}$$

$$\alpha_\mathrm{vib,O} = 4{,}3778\, f^2\, c^{-1}\left(f_\mathrm{r\,O} + f^2 / f_\mathrm{r\,O}\right)^{-1}\left(\frac{T}{T_{20}}\right)^{-2}\exp(-2239{,}1/T)$$

$$\alpha_\mathrm{vib,N} = 36{,}6624\, f^2\, c^{-1}\left(f_\mathrm{r\,N} + f^2 / f_\mathrm{r\,N}\right)^{-1}\left(\frac{T}{T_{20}}\right)^{-2}\exp(-3352{,}0/T)$$

Step 5

Calculate the air attenuation coefficient α in nepers per metre (Np/m):

$$\alpha = \alpha_\mathrm{cl} + \alpha_\mathrm{rot} + \alpha_\mathrm{vib,O} + \alpha_\mathrm{vib,N} = f^{\,2}\left[18{,}42\times 10^{-12}\left(\frac{p_\mathrm{s}}{p_\mathrm{s,\,r}}\right)^{-1}\left(\frac{T}{T_{20}}\right)^{\frac{1}{2}}\right.$$

$$\left. + \left(\frac{T}{T_{20}}\right)^{-2}\left(\frac{4{,}3778}{c}\,\frac{\exp(-2239{,}1/T)}{f_\mathrm{r\,O} + (f^{\,2}/f_\mathrm{r\,O})} + \frac{36{,}6624}{c}\,\frac{\exp(-3352{,}0/T)}{f_\mathrm{rN} + (f^{\,2}/f_\mathrm{rN})}\right)\right]$$

The accuracy of the calculated air attenuation coefficient is estimated to be ±10 % for variations within the following ranges:

Air temperature:	−20 °C to 50 °C
Static pressure:	less than 200 kPa
Molar fraction of water vapour:	$0{,}5\times 10^{-3}$ to 50×10^{-3}

Frequency-to-pressure ratio: 0,4 Hz/kPa to 10^4 Hz/kPa

Table B.1 gives values for the attenuation of sound pressure in air calculated according to ISO 9613-1 under the environmental conditions most relevant for reciprocity free-field calibrations in a laboratory.

The tabulated values are expressed in decibels per metre as 8,686 α.

Table B.1 – Values for attenuation of sound pressure in air (in dB/m)

f kHz	t = 21 °C, p_s = 101,325 kPa			t = 23 °C, p_s = 101,325 kPa			t = 25 °C, p_s = 101,325 kPa		
	H=25 %	H=50 %	H=80 %	H=25 %	H=50 %	H=80 %	H=25 %	H=50 %	H=80 %
1,0	0,005 4	0,004 8	0,005 4	0,005 4	0,005 2	0,005 9	0,005 4	0,005 7	0,006 3
1,25	0,007 5	0,005 9	0,006 3	0,007 2	0,006 2	0,006 9	0,007 0	0,006 7	0,007 6
1,6	0,011 1	0,007 5	0,007 7	0,010 4	0,007 8	0,008 3	0,009 9	0,008 2	0,009 1
2,0	0,016 2	0,009 9	0,009 3	0,014 9	0,009 9	0,009 9	0,014 0	0,010 2	0,010 7
2,5	0,024 0	0,013 4	0,011 6	0,022 0	0,013 2	0,012 1	0,020 3	0,013 2	0,012 9
3,15	0,036 5	0,019 2	0,015 3	0,033 2	0,018 4	0,015 5	0,030 4	0,018 0	0,016 1
4,0	0,056 5	0,028 7	0,021 2	0,051 4	0,027 1	0,021 0	0,046 9	0,025 9	0,021 2
5,0	0,084 6	0,042 6	0,029 9	0,077 3	0,039 7	0,029 1	0,070 6	0,037 4	0,028 7
6,3	0,126 7	0,064 9	0,044 1	0,117 0	0,060 1	0,042 1	0,107 6	0,056 1	0,040 7
8,0	0,188 2	0,101 0	0,067 3	0,176 7	0,093 3	0,063 5	0,164 5	0,086 6	0,060 5
10,0	0,264 3	0,152 7	0,101 3	0,253 9	0,141 1	0,094 9	0,240 5	0,130 8	0,089 6
12,5	0,357 8	0,229 2	0,153 5	0,353 7	0,213 1	0,143 4	0,342 9	0,198 0	0,134 7
16,0	0,477 1	0,354 1	0,243 5	0,488 5	0,332 7	0,227 5	0,488 9	0,311 5	0,213 2
20,0	0,592 9	0,513 9	0,368 2	0,626 6	0,490 1	0,345 2	0,646 8	0,464 1	0,324 0
25,0	0,712 3	0,725 6	0,551 4	0,773 7	0,706 1	0,520 7	0,822 4	0,679 4	0,491 0
31,5	0,842 1	1,001 9	0,824 4	0,933 2	0,999 8	0,787 6	1,016 6	0,982 8	0,749 1
40,0	0,994 7	1,344 5	1,219 1	1,113 6	1,379 5	1,184 7	1,232 6	1,391 5	1,141 9
50,0	1,175 8	1,713 5	1,708 3	1,315 7	1,800 7	1,693 0	1,463 6	1,861 2	1,659 4

Annex C
(informative)

Environmental influence on the sensitivity of microphones

C.1 General

Annex C gives information on the influence of static pressure and temperature on the free-field sensitivity of type LS1P and LS2P microphones. At present, such data are not available for other types of LS microphones.

A comprehensive description of the influence of the environmental conditions on the pressure sensitivity of microphones is given in Annex D of IEC 61094-2:2009. In addition to this influence, the radiation impedance and the diffraction around the microphone also depend on the environmental conditions.

Constructional details of the microphone determine the relative influence of the environmental conditions. The speed of sound, the density and the viscosity of air are considered linear functions of temperature and/or static pressure. The resulting static pressure and temperature coefficients of the microphone are then considered to be determined by the ratio of the free-field sensitivity at reference conditions to the free-field sensitivity at the relevant static pressure and temperature, respectively. The examples apply to the free-field sensitivity for sound propagation along the principal axis toward the front of diaphragm.

C.2 Dependence on static pressure

Examples of the static pressure coefficient referring to the pressure sensitivity of microphones are shown in Figure D.1 of IEC 61094-2:2009. The additional influence from the radiation impedance will modify this figure primarily by lowering the resonance frequency slightly. Thus, in the absence of a detailed knowledge of the static pressure coefficients for the free-field sensitivities the corresponding values for the pressure sensitivities may be used with an increased uncertainty at high frequencies. In general, the static pressure coefficient depends on constructional details of the microphone and the actual values may differ considerably for two microphones of different manufacture although the microphones may belong to the same type. Consequently, the static pressure coefficients shown on Figure D.1 of IEC 61094-2:2009 should not be applied to individual microphones.

The low-frequency value of the static pressure coefficient generally lies between −0,01 dB/kPa and −0,02 dB/kPa for LS1P microphones, and between −0,003 dB/kPa and −0,008 dB/kPa for LS2P microphones.

C.3 Dependence on temperature

Examples of the temperature coefficient referring to the pressure sensitivity of microphones are shown in Figure D.2 of IEC 61094-2:2009. For the free-field sensitivity, temperature variations influence the free-field sensitivity in two ways: via the additional radiation impedance and via the scattering factor $\underline{S}(f,\theta)$ (see Formula (4)).

The influence on the free-field sensitivity arising from the radiation impedance follows the same procedure as outlined in C.2 above, i.e. the temperature coefficients valid for the pressure sensitivities may be applied with an increased uncertainty at high frequencies.

The influence of temperature on the speed of sound, i.e. on the wavelength, also affects the scattering factor $\underline{S}(f,\theta)$ (see Formula (4)). This effect will depend on the angle of sound incidence and may lead to high values at high frequencies at certain angles of minimum sensitivity. For normal incidence of sound, IEC TS 61094-7 describes the free-field to pressure sensitivity level differences for type LS1P and LS2P microphones and their dependence on temperature.

The low-frequency value of the temperature coefficient generally lies between −0,005 dB/K and +0,005 dB/K for both LS1P and LS2P microphones.

Annex D
(informative)

Application of time selective techniques for removal of unwanted reflections and acoustic interference between microphones

D.1 General

The practical implementation of the free-field reciprocity method can suffer from a number of problems that will have a degrading effect on the accuracy of the free-field sensitivity determined from these measurements. These perturbations include electrical cross-talk, reflections from the mechanical elements used to hold the microphones in place and from room walls, and the acoustic interference between microphones. These perturbations can be totally or partially removed by filtering in the time domain (time-selective or time-windowing techniques).

The basic principles of filtering in the time domain relevant for this part of IEC 61094 are described in IEC 61094-8:2012, B.1, B.2 and B.3.

D.2 Practical considerations

D.2.1 Signal-to-noise ratio

It is common, due to the very low signal-to-noise ratio (SNR) during the measurement of the electrical transfer impedance, that pure sinusoidal signals are used for driving the transmitter microphone. Large driving signals can introduce harmonic artefacts that will affect the level of the fundamental frequency component, and thus should be avoided. A possibility for improving the SNR is to apply narrow-band filtering either by hardware filters, by spectral averaging, or by synchronous averaging in the time domain.

Signal-to-noise ratio is frequency dependent. At low and very high frequencies, the efficiency of microphones as sound transmitters is very low, and the resulting SNR is poor; it would require impractically long averaging times to obtain a sufficiently narrow filtering bandwidth. Acceptable SNR's are generally obtained in the frequency range from 0,1 times to 3 times the resonance frequency of the microphones.

This presents a limitation on the frequency range where measurements of the electrical transfer impedance yield an acceptable accuracy, regardless of the signal type used.

D.2.2 Reflections from walls and measurement rig

The instant in which reflections from walls and other mechanical elements of the measurement rig reach the microphones helps to decide how long the total impulse response should be in order to fully separate early and late reflections from the direct impulse response. Besides the practical design considerations that define the position of potentially reflective elements in the measurement set-up, a decision on the sound absorbing material used in the measurement rooms will have an influence in the selection of the measurement parameters.

Circular convolution can occur when the transfer function is measured in the frequency domain, and then transformed into the time domain. Consequently, for insufficiently long impulse responses, or inversely insufficiently small frequency spacing, late-arriving secondary or tertiary reflections at the receiver microphone will be missed out, which then fold over the obtained impulse response and most likely affect the final results. This is particularly critical in small rooms. The problem can be minimized by

- decreasing the size of the frequency steps, hence increasing the length of the impulse response (this will also improve sampling of the reflections and other disturbances), and
- having the walls of the measurement room covered with absorbent material that reduces the amplitude of the incident wave by at least 30 dB.

Circular convolution will not occur when using sweeps providing that sufficient zero-padding is used. However, it is important to ensure that the impulse response is sufficiently long as to include all reflections.

D.3 Frequency limitations

D.3.1 General

Swept-sine signals can be used to measure the frequency response in a finite frequency range that can include low frequencies, and up to a frequency limit prescribed by the instrumentation used. Measurements based on pure tones or broadband signals, like pseudo-random noise, can also start at low frequencies, and go up to the high frequency limit dictated by the instrumentation. Due to the signal-to-noise limitations discussed in D.2.1, the practical difficulties of including low frequency measurements may outweigh the benefits.

In addition, the nature of each measurement method requires that low frequency limitations are treated differently.

D.3.2 Measurements based on frequency sweeps

Sweep signals can be designed to have a frequency content confined within a finite frequency band. The signal processing resulting in the determination of the impulse response is based on the deconvolution of the measured response with the inverse filter; therefore, the design of the signal can benefit from the following considerations.

- The inverse filter will amplify those frequency components outside of the frequency range of interest. This can potentially mask the retrieved impulse response if the signal-to-noise ratio (SNR) outside the frequencies of interest is not high enough to counterbalance the amplification provided by the inverse filter.
- Any discontinuity in the excitation signal will yield artefacts in the form of impulsive noise. This is particularly important when designing the onset and end of the excitation signal. Tapering the start and end of the excitation signal with a time window can avoid such problems.
- If the time-frequency selectivity featured by sweep signals is to be fully exploited, particularly for distortion analysis, it is important to implement the deconvolution process as a linear convolution. To do this in the frequency domain by means of the Discrete Fourier Transform (DFT) or the Fast Fourier Transform (FFT) algorithms, one has to add zeroes at the end of the temporal signals (this procedure is often referred to as “zero-padding”) so that there is no wrap-around effect when performing the convolution.

D.3.3 Measurements based on pure tones

When the frequency response is measured with pure tones, the start and end points of the frequency range measured can be chosen arbitrarily. Due to the presence of cross-talk, background noise, and the poor transmission capabilities of the microphones, it is impractical and possibly time-consuming to make measurements at frequencies below one-eighth of the resonance frequency for LS1 and LS2 microphones.

The highest measurement frequency should be chosen such that a more realistic representation of the direct impulse response between microphones is obtained. This usually occurs when the highest measured frequency is more than 2 to 3 times the resonance frequency of the microphones.

D.4 Generating missing portions of the frequency response previous to transforming to the time-domain.

D.4.1 General

To make the transformation from the frequency domain to the time domain and obtain a representation of the impulse response that is free of artefacts, it is necessary to measure the transfer impedance at frequencies from −∞ to +∞ (or from 0 to +∞ when using a one-sided frequency response). This cannot be done in practice, and any measurement will be subject to well-defined frequency limits, (f_{min}, f_{max}) as discussed above. A less accurate but still reliable representation can be obtained by using two procedures: filling the missing frequency ranges with theoretically determined values of the frequency response, and applying either a low-pass frequency filter or a band-pass frequency filter before the transformation to the time domain.

In principle, the measured frequency response can be represented as the multiplication of the infinite frequency response and a rectangular band-pass frequency filter. However, the use of this approach is not recommended because such a filter has poorly attenuated side lobes that can result in an impulse response contaminated with spurious components.

D.4.2 Missing frequencies below the minimum measurement frequency

The electrical transfer impedance from f = 0 to $f = f_{\text{min}}$ can be generated using an expression obtained from re-arranging Formula (7):

$$\frac{\underline{U}_2}{\underline{i}_1} = \mathrm{j}\,\frac{\rho f}{2d_{12}}\,\underline{M}_{\text{f,1}}\,\underline{M}_{\text{f,2}}\,\mathrm{e}^{-\mathrm{j}kd_{12}}\,\mathrm{e}^{-\alpha d_{\text{m12}}} \tag{D.1}$$

At low frequencies up to about a quarter of the resonance frequency, the free-field sensitivity can be calculated by using Formula (4). At these frequencies the load of the radiation impedance can be neglected, and the free-field sensitivity can be calculated from the product of the pressure sensitivity and the scattering factor. Furthermore, at these frequencies air absorption can also be neglected in Formula (D.1).

The pressure sensitivity can be determined experimentally from electrostatic actuator measurements or reciprocity calibration. However, it is important to note that in a free-field calibration, the static pressure equalization tube of the microphone is exposed to the sound field. The pressure sensitivity can also be determined analytically from lumped parameter models.

The diffraction factor can be determined either numerically, using the Boundary Element Method, the Finite Element Method or any other integral formulation, or it can be determined experimentally from measurements in a large standing wave tube.

NOTE In order to avoid strong discontinuities between the calculated and the measured transfer impedances, a smoothing transition can be achieved by defining an overlap frequency range in which the frequency response is calculated as a progressive gliding average.

D.4.3 Missing frequencies above the maximum measured frequency

The high frequency data cannot in practice be determined from Formula (D.1) due to the many complexities of the behaviour of the microphone: resonances in the back cavity, viscous losses, etc. A simplified approach may be to consider the microphone as a single degree of freedom system, where the sensitivity falls by 12 dB per octave above its resonance frequency. A simple and practical approach is to extrapolate the complex frequency response using the last few measurement points in which the measured frequency response decays smoothly.

D.4.4 Filtering the extended frequency response

An additional measure to accelerate the decay of the frequency response at high frequencies is to apply a low-pass frequency filter. A low-pass filter designed for this purpose should have highly attenuated secondary lobes (at least 80 dB), minimal ripple (0,01 dB maximum), and linear phase. It is also recommended that the roll-off frequency of the filter lies within the extrapolated frequency range.

NOTE A band-pass having similar properties to the low-pass filter can also be used.

Bibliography

Relevant for Annex A:

WAGNER, R.P., and NEDZELNITSKY, V. Determination of acoustic center correction values for type LS2aP microphones at normal incidence, *J. Acoust. Soc. Am.* **104**, 1998, 192-203

BARRERA-FIGUEROA, S., RASMUSSEN, K., and JACOBSEN, F. *The acoustic center of laboratory standard microphones J. Acoust. Soc. Am.* **120**, 2006, 2668-2675

RODRIGUES, D., DUROCHER, J.-N., BRUNEAU, M., and BRUNEAU A.-M., A new method for the determination of the acoustic center of acoustic transducers, *Acta Acustica united with Acustica* **96**, 2010, 300-305

Relevant for Annex D:

A general bibliography concerning time selective methods applied to microphone calibration is presented in IEC 61094-8. The bibliography below supplements this with literature that is specifically related to the application of time-selective techniques to free-field reciprocity calibration.

IEC 61094-8:2012, *Measurement microphones – Part 8: Methods for determining the free-field sensitivity of working standard microphones by comparison*

LAMBERT, J.-M., and DUROCHER, J.-N., *Analyse des perturbations acoustiques lors de l'étalonnage en champ libre des microphones étalons a condensateurs dits d'un pouce par la technique de la réciprocité*, Laboratoire National d'Essais, 1989

VORLÄNDER, M., and BIETZ, H. Novel broad band reciprocity technique for simultaneous free-field and diffuse-field microphone calibration, *Acustica* **80**, 1994, 365-377

BARRERA-FIGUEROA, S., RASMUSSEN, K., and JACOBSEN, F. A time-selective technique for free-field reciprocity calibration of condenser microphones, *J. Acoust. Soc. Am.* **114**, 2003, 1467-1476

KWON, H.S., SUH, S.J., and SUH, J.G. Frequency Windowing Technique for Reducing Multi-Path Noise in Free-Field Reciprocity Microphone Calibration Method, *Key Engineering Materials* **321-323**, 2006, 1245-1248

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Copyright in BSI publications

Storing and using standards

Standards purchased in soft copy format:

- A British Standard purchased in soft copy format is licensed to a sole named user for personal or internal company use only.
- The standard may be stored on more than 1 device provided that it is accessible by the sole named user only and that only 1 copy is accessed at any one time.
- A single paper copy may be printed for personal or internal company use only.

Standards purchased in hard copy format:

- A British Standard purchased in hard copy format is for personal or internal company use only.
- It may not be further reproduced – in any format – to create an additional copy. This includes scanning of the document.

If you need more than 1 copy of the document, or if you wish to share the document on an internal network, you can save money by choosing a subscription product (see 'Subscriptions').

Reproducing extracts

For permission to reproduce content from BSI publications contact the BSI Copyright & Licensing team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email subscriptions@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Useful Contacts

Customer Services
Tel: +44 345 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 345 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

bsi.