BS EN 61094-2:2009

BSI British Standards

Electroacoustics — Measurement microphones —

Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique

National foreword

This British Standard is the UK implementation of EN 61094-2:2009. It is identical to IEC 61094-2:2009. It supersedes BS EN 61094-2:1994 which is withdrawn.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.

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English version

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

Electroacoustique -
Microphones de mesure -
Partie 2: Méthode primaire pour l'étalonnage en pression des microphones étalons de laboratoire par la méthode de réciprocité
(CEI 61094-2:2009)

Elektroakustik -
Messmikrofone -
Teil 2: Primärverfahren zur Druckkammer-Kalibrierung von Laboratoriums-Normalmikrofonen nach der Reziprozitätsmethode
(IEC 61094-2:2009)

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

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CENELEC

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

Central Secretariat: avenue Marnix 17, B - 1000 Brussels

Foreword

The text of document 29/671/FDIS, future edition 2 of IEC 61094-2, prepared by IEC TC 29, Electroacoustics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61094-2 on 2009-03-01.

This European Standard supersedes EN 61094-2:1993.

EN 61094-2:2009 includes the following significant technical changes with respect to EN 61094-2:1993:

– an update of Clause 6 to fulfil the requirements of ISO/IEC Guide 98-3;

– an improvement of the heat conduction theory in Annex A;

– a revision of Annex F: Physical properties of humid air.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2009-12-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2012-03-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61094-2:2009 was approved by CENELEC as a European Standard without any modification.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application 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.

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

Publication	Year	Title	EN/HD	Year
IEC 61094-1	2000	Measurement microphones - Part 1: Specifications for laboratory standard microphones	EN 61094-1	2000
ISO/IEC Guide 98-3	-[1)]	Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)	-	-

[1)] Undated reference.

CONTENTS

ELECTROACOUSTICS –
MEASUREMENT MICROPHONES –

Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique

1 Scope

This part of International Standard IEC 61094

– is applicable to laboratory standard microphones meeting the requirements of IEC 61094-1 and other types of condenser microphone having the same mechanical dimensions;
– specifies a primary method of determining the complex pressure sensitivity so as to establish a reproducible and accurate basis for the measurement of sound pressure.

All quantities are expressed in SI units.

2 Normative references

The following referenced documents are indispensable for the application 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 61094-1:2000, *Measurement microphones – Part 1: Specifications for laboratory standard microphones*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*[1]

3 Terms and definitions

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

3.1
reciprocal microphone
linear passive microphone for which the open circuit reverse and forward transfer impedances are equal in magnitude

3.2
phase angle of pressure sensitivity of a microphone
for a given frequency, the phase angle between the open-circuit voltage and a uniform sound pressure acting on the diaphragm

NOTE Phase angle is expressed in degrees or radians (° or rad).

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1 ISO/IEC Guide 98-3:2008 is published as a reissue of the Guide to the expression of uncertainty in measurement (GUM), 1995.

3.3
electrical transfer impedance
for a system of two acoustically coupled microphones the quotient of the open-circuit voltage of the microphone used as a receiver by the input current through the electrical terminals of the microphone used as a transmitter

NOTE 1 Electrical transfer impedance is expressed in ohms (Ω).

NOTE 2 This impedance is defined for the ground-shield configuration given in 7.2 of IEC 61094-1:2000.

3.4
acoustic transfer impedance
for a system of two acoustically coupled microphones the quotient of the sound pressure acting on the diaphragm of the microphone used as a receiver by the short-circuit volume velocity produced by the microphone used as a transmitter

NOTE Acoustic transfer impedance is expressed in pascal-seconds per cubic metre ($Pa \cdot s/m^3$).

3.5
coupler
device which, when fitted with microphones, forms a cavity of predetermined shape and dimensions acting as an acoustic coupling element between the microphones

4 Reference environmental conditions

The reference environmental conditions are:

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

5 Principles of pressure 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, of which one shall be reciprocal.

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

5.1.2 General principles using three microphones

Let two of the microphones be connected acoustically by a coupler. 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 pressure sensitivities of the two coupled microphones can be determined. Using pair-wise combinations of three microphones marked (1), (2) and (3), three such mutually independent products are available, from which an expression for the pressure 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 connected acoustically by a coupler, and the product of the pressure sensitivities of the two microphones be determined (see 5.1.2). Next, let the two microphones be presented to the same sound pressure, set up by the auxiliary sound source. The ratio of the two output voltages will then equal the ratio of the two pressure sensitivities.

Thus, from the product and the ratio of the pressure sensitivities of the two microphones, an expression for the pressure sensitivity of each of the two microphones can be derived.

NOTE In order to obtain the ratio of pressure sensitivities, a direct comparison method may be used, and the auxiliary sound source may be a third microphone having mechanical or acoustical characteristics which differ from those of the microphones being calibrated.

5.2 Basic expressions

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

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

where

$\underline{p}$	is the sound pressure, uniformly applied, at the acoustical terminals (diaphragm) 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 ($V \cdot s \cdot m^{-3}$), $\underline{M}_p$ being the pressure sensitivity of the microphone in volts per pascal ($V \cdot Pa^{-1}$).

NOTE Underlined symbols represent complex quantities.

Equations (1) may then be rewritten as:

$$\begin{aligned} \underline{Z}_e\,\underline{i} + \underline{M}_p\,\underline{Z}_a\,\underline{q} &= \underline{U} \\ \underline{M}_p\,\underline{Z}_a\,\underline{i} + \underline{Z}_a\,\underline{q} &= \underline{p} \end{aligned} \qquad (1a)$$

which constitute the equations of reciprocity for the microphone.

Let microphones (1) and (2) with the pressure sensitivities $\underline{M}_{p,1}$ and $\underline{M}_{p,2}$ be connected acoustically by a coupler. From Equations (1a) it is seen that a current $\underline{i}_1$ through the electrical terminals of microphone (1) will produce a short-circuit volume velocity ($\underline{p}$ = 0 at the diaphragm) of $\underline{M}_{p,1}\,\underline{i}_1$ and thus a sound pressure $\underline{p}_2 = \underline{Z}_{a,12}\,\underline{M}_{p,1}\,\underline{i}_1$ at the acoustical terminals of microphone (2), where $\underline{Z}_{a,12}$ is the acoustic transfer impedance of the system.

The open-circuit voltage of microphone (2) will then be:

$$\underline{U}_2 = \underline{M}_{p,2} \cdot \underline{p}_2 = \underline{M}_{p,1}\,\underline{M}_{p,2}\,\underline{Z}_{a,12}\,\underline{i}_1$$

Thus the product of the pressure sensitivities is given by:

$$\underline{M}_{\text{p},1}\underline{M}_{\text{p},2} = \frac{1}{\underline{Z}_{\text{a},12}}\frac{\underline{U}_2}{\underline{i}_1} \qquad (2)$$

5.3 Insert voltage technique

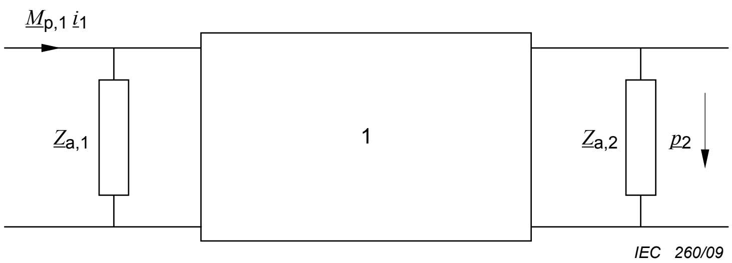
The insert voltage technique is used to determine the open-circuit voltage of a microphone when it is electrically loaded.

Let a microphone having a certain open-circuit voltage and internal impedance be connected to a 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 Evaluation of the acoustic transfer impedance

The acoustic transfer impedance $\underline{Z}_{\text{a},12} = \underline{p}_2/(\underline{M}_{\text{p},1}\underline{i}_1)$ can be evaluated from the equivalent circuit in Figure 1, where $\underline{Z}_{\text{a},1}$ and $\underline{Z}_{\text{a},2}$ are the acoustic impedances of microphones (1) and (2) respectively.



Key

1 Coupler

Figure 1 – Equivalent circuit for evaluating the acoustic transfer impedance $\underline{Z}_{\text{a},12}$

In several cases, $\underline{Z}_{\text{a},12}$ can be evaluated theoretically. Assume the sound pressure to be the same at any point inside the coupler (this will take place when the physical dimensions of the coupler are very small compared to the wavelength). The gas in the coupler then behaves as a pure compliance and, from the equivalent circuit in Figure 2, $\underline{Z}_{\text{a},12}$ is given by $\underline{Z}'_{\text{a},12}$ (assuming adiabatic compression and expansion of the gas):

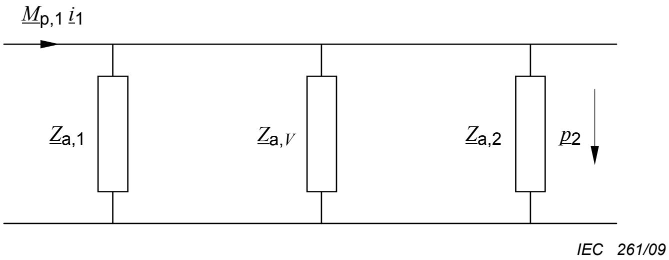


Figure 2 – Equivalent circuit for evaluating $\underline{Z}'_{a,12}$ when coupler dimensions are small compared with wavelength

$$\frac{1}{\underline{Z}'_{a,12}} = \frac{1}{\underline{Z}_{a,V}} + \frac{1}{\underline{Z}_{a,1}} + \frac{1}{\underline{Z}_{a,2}} = \mathrm{j}\omega\left(\frac{V}{\kappa\, p_s} + \frac{\underline{V}_{e,1}}{\kappa_r\, p_{s,r}} + \frac{\underline{V}_{e,2}}{\kappa_r\, p_{s,r}}\right) \tag{3}$$

where

V	is the total geometrical volume of the coupler in cubic metres (m^3);
$\underline{V}_{e,1}$	is the equivalent volume of microphone (1) in cubic metres (m^3);
$\underline{V}_{e,2}$	is the equivalent volume of microphone (2) in cubic metres (m^3);
$\underline{Z}_{a,V} = \dfrac{\kappa p_s}{\mathrm{j}\omega V}$	is the acoustic impedance of the gas enclosed in the coupler in pascal-seconds per cubic metre ($Pa \cdot s/m^3$);
ω	is the angular frequency in radians per second (rad/s);
p_s	is the static pressure in pascals (Pa);
$p_{s,r}$	is the static pressure at reference conditions in pascals (Pa);
κ	is the ratio of the specific heat capacities at measurement conditions;
κ_r	is κ at reference conditions.

Values for κ and κ_r in humid air can be derived from equations given in Annex F.

At higher frequencies, when the dimensions are not sufficiently small compared with the wavelength, the evaluation of $\underline{Z}_{a,12}$ generally becomes complicated. However, if the shape of the coupler is cylindrical and the diameter the same as that of the microphone diaphragms, then, at frequencies where plane-wave transmission can be assumed, the whole system can be considered as a homogeneous transmission line (see Figure 3).

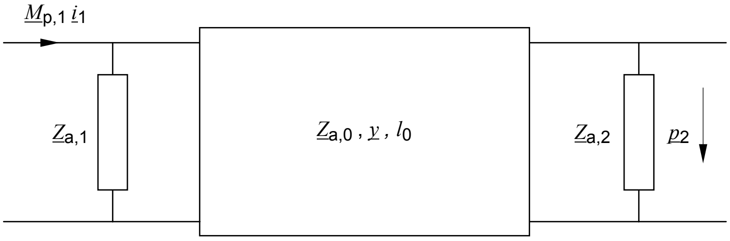


Figure 3 – Equivalent circuit for evaluating $\underline{Z}'_{a,12}$ when plane wave transmission in the coupler can be assumed

$\underline{Z}_{a,12}$ is then given by $\underline{Z}'_{a,12}$ (assuming adiabatic compression and expansion of the gas):

$$\frac{1}{\underline{Z}'_{a,12}} = \frac{1}{\underline{Z}_{a,0}}\left[\left(\frac{\underline{Z}_{a,0}}{\underline{Z}_{a,1}} + \frac{\underline{Z}_{a,0}}{\underline{Z}_{a,2}}\right)\cosh \underline{\gamma} l_0 + \left(1 + \frac{\underline{Z}_{a,0}}{\underline{Z}_{a,1}}\frac{\underline{Z}_{a,0}}{\underline{Z}_{a,2}}\right)\sinh \underline{\gamma} l_0\right] \quad (4)$$

where

$\underline{Z}_{a,0}$	is the acoustic impedance of plane waves in the coupler. If losses in the coupler are neglected, then $\underline{Z}_{a,0} = \rho c / S_0$;
ρ	is the density of the gas enclosed in kilograms per cubic metre (kg·m^{-3});
c	is the free-space speed of sound in the gas in metres per second (m·s^{-1});
S_0	is the cross-sectional area of the coupler in square metres (m^2);
l_0	is the length of the coupler, i.e. the distance between the two diaphragms in metres (m);
$\underline{\gamma} = \alpha + j\beta$	is the complex propagation coefficient in metres to power minus one (m^{-1}).

Values for ρ and c in humid air can be derived from equations given in Annex F.

The real part of $\underline{\gamma}$ accounts for the viscous losses and heat conduction at the cylindrical surface and the imaginary part is the angular wave number.

If losses are neglected, $\underline{\gamma}$ may be approximated by putting α equal to zero and β equal to ω/c in Equation (4).

Allowance shall be made for any air volume associated with the microphones that is not enclosed by the circumference of the coupler and the two diaphragms (see 7.3.3.1).

5.5 Heat-conduction correction

The evaluation of $\underline{Z}'_{a,12}$ in the preceding subclause assumes adiabatic conditions in the coupler. However, in practice, the influence of heat conduction at the walls of the coupler causes departure from purely adiabatic conditions, especially for small couplers and low frequencies.

At low frequencies, where the sound pressure can be considered the same at any point and under the assumption that the walls remain at a constant temperature, the influence of the heat conduction losses can be calculated and expressed in terms of a complex correction factor $\underline{\Delta}_H$ to the geometrical volume V in Equation (3). Expressions for the correction factor $\underline{\Delta}_H$ are given in Annex A.

At high frequencies, wave-motion will be present inside the coupler and the sound pressure will no longer be the same at all points. For right-cylindrical couplers where the transmission line theory can be applied (see 5.4), the combined effect of heat conduction and viscous losses along the cylindrical surface can be accounted for by the complex propagation coefficient and acoustic impedance for plane-wave propagation in the coupler. The additional heat conduction at the end surfaces of the coupler, the microphone diaphragms, can be accounted for by including further components in the acoustic impedances of the microphones. Expressions for the complex propagation coefficient and acoustic impedance for plane-wave propagation are given in Annex A.

5.6 Capillary tube correction

The coupler is usually fitted with capillary tubes in order to equalize the static pressure inside and outside the coupler. Two such capillary tubes also permit the introduction of a gas other than air.

The acoustic input impedance of an open capillary tube is given by:

$$\underline{Z}_{a,C} = \underline{Z}_{a,t} \tanh \underline{\gamma}\, l_C \tag{5}$$

where

$\underline{Z}_{a,t}$ is the complex acoustic wave impedance of an infinite tube in pascal-seconds per cubic metre (Pa·s·m^{-3});

l_C is the length of the tube in metres (m).

The shunting effect of the capillary tubes can be taken into account by introducing a complex correction factor $\underline{\Delta}_C$ to the acoustic transfer impedances given in Equations (3) and (4):

$$\underline{\Delta}_C = 1 + n \frac{\underline{Z}''_{a,12}}{\underline{Z}_{a,C}} \tag{6}$$

where

n is the number of identical capillary tubes used;

$\underline{Z}''_{a,12}$ is the acoustic transfer impedance $\underline{Z}'_{a,12}$ corrected for heat conduction according to 5.5.

An expression for the acoustic input impedance $\underline{Z}_{a,C}$ of an open capillary tube is given in Annex B.

5.7 Final expressions for the pressure sensitivity

5.7.1 Method using three microphones

Let the electrical transfer impedance $\underline{U}_2/\underline{i}_1$ (see 5.2) be denoted by $\underline{Z}_{e,12}$ with similar expressions for other pairs of microphones.

Taking into account the corrections given in 5.5 and 5.6, the final expression for the modulus of the pressure sensitivity of microphone (1) is:

$$\left|\underline{M}_{p,1}\right| = \left\{ \left| \frac{\underline{Z}_{e,12}\,\underline{Z}_{e,31}}{\underline{Z}_{e,23}} \right| \left| \frac{\underline{Z}''_{a,23}}{\underline{Z}''_{a,12}\,\underline{Z}''_{a,31}} \right| \left| \frac{\underline{\Delta}_{C,12}\,\underline{\Delta}_{C,31}}{\underline{\Delta}_{C,23}} \right| \right\}^{1/2} \tag{7}$$

Similar expressions apply for microphones (2) and (3).

The phase angle of the pressure sensitivity for each microphone is determined by a similar procedure from the phase angle of each term in the above expression.

NOTE When complex quantities are expressed in terms of modulus and phase, the phase information should be referred to the full four-quadrant phase range, i.e. 0 - 2π rad or 0 – 360°.

5.7.2 Method using two microphones and an auxiliary sound source

If only two microphones and an auxiliary sound source are used, the final expression for the modulus of the pressure sensitivity is:

$$\left|\underline{M}_{p,1}\right| = \left| \frac{\underline{M}_{p,1}}{\underline{M}_{p,2}} \frac{\underline{Z}_{e,12}}{\underline{Z}''_{a,12}} \underline{\Delta}_C \right|^{1/2} \tag{8}$$

where the ratio of the two pressure sensitivities is measured by comparison against the auxiliary source, see 5.1.3.

6 Factors influencing the pressure sensitivity of microphones

6.1 General

The pressure sensitivity of a condenser microphone depends on polarizing voltage and environmental conditions.

The basic mode of operation of a polarized condenser 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 charging 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.

Further, the definition of the pressure 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 condenser 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 Ground-shield reference configuration

According to 3.3 of IEC 61094-1:2000, the open-circuit voltage shall be measured at the electrical terminals of the microphone when it is attached to a specified ground-shield configuration using the insert voltage technique described in 5.3 above. Specifications for ground-shield configurations for laboratory standard microphones are given in IEC 61094-1:2000.

The appropriate ground-shield configuration shall apply to both transmitter and receiver microphones during the calibration, and the shield should be connected to ground potential.

If any other arrangement is used, the results of a calibration shall be referred to the reference ground-shield 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.

6.4 Pressure distribution over the diaphragm

The definition of the pressure sensitivity assumes that the sound pressure over the diaphragm is applied uniformly. The output voltage of a microphone presented with a non-uniform pressure distribution over the surface of the diaphragm will differ from the output voltage of the microphone when presented with a uniform pressure distribution having the same mean value, because usually the microphone is more sensitive to a sound pressure at the centre of the diaphragm. This difference will vary for microphones with various different non-uniformities of tension distribution on the diaphragm.

For cylindrical couplers, as described in Annex C, both longitudinal and radial wave motions (symmetric as well as asymmetric) will be present. The radial wave motion will result in a non-uniform pressure distribution over the diaphragm. It will be generated when the source differs from a true piston source covering the whole end surface of the coupler or when the combined microphone/coupler geometry is not a perfect right angle cylinder. In addition asymmetric radial wave motion is also generated by the transmitter microphone by imperfections in the backplate/diaphragm geometry or in the diaphragm tension and homogeneity.

It is recommended that the sound pressure distribution during a calibration should be uniform to better than ± 0,1 dB over the surface of the diaphragm. However, it is difficult to control this condition in an actual calibration set-up due to the geometrical imperfection of real microphones and couplers. Although radial wave motion can never be avoided because the velocity distribution of the transmitter microphone differs from that of a true piston, couplers having the same diameter as that of the microphone diaphragm will exhibit the smallest amount of radial wave motion and be less sensitive to geometrical imperfections than couplers with larger diameters.

However, when a calibration at high frequencies with a high accuracy is necessary, it may be preferable to use more than one coupler with different dimensions to assess the true sensitivity of the microphones and to apply a theoretically based correction for the radial wave-motion effects.

6.5 Dependence on environmental conditions

6.5.1 Static pressure

The acoustic resistance and mass of the gas between the diaphragm and backplate, the compliance of the cavity behind the diaphragm and thus the pressure sensitivity of the microphone, depend on the static pressure. This dependence is a function of frequency. It can be determined for a microphone under test by making reciprocity calibrations at different static pressures.

Annex D contains information on the influence of static pressure on the pressure sensitivity of laboratory standard condenser microphones.

6.5.2 Temperature

The acoustic resistance and mass of the gas between diaphragm and backplate and thus the pressure sensitivity of the microphone, depend on the temperature. In addition the mechanical dimensions of the microphone depend on the temperature and the sensitivity of the microphone depends on the mechanical tension in the diaphragm and on the spacing between diaphragm and backplate. The total effect of these dependencies is a function of frequency. The combined dependence can be determined for a microphone under test by making reciprocity calibrations at different temperatures.

Annex D contains information on the influence of temperature on the pressure sensitivity of laboratory standard condenser microphones.

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

6.5.3 Humidity

Although the thermodynamic state of the air enclosed in the cavity behind the diaphragm of the microphone depends slightly on humidity, an influence on the sensitivity has not been observed for laboratory standard microphones, provided condensation does not take place.

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 may deteriorate under excessively humid conditions, particularly if the material is contaminated (see also 7.3.3.3). The surface resistance has a noticeable effect on the sensitivity of the microphone at low frequencies, especially on the phase response.

6.5.4 Transformation to reference environmental conditions

When reporting the results of a calibration, the pressure sensitivity should be referred to the reference environmental conditions if reliable correction data are available.

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.

7 Calibration uncertainty components

7.1 General

In addition to the factors mentioned in Clause 6 which affect the pressure 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 ground shield reference configuration, see 6.3, 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 by a voltage ratio and the calibrated series impedance.

The voltage used to excite the transmitter microphone shall be such that the effect of harmonics, from this source or generated by the microphone, on the uncertainty in the determination of the pressure sensitivity 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 pressure sensitivity.

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

NOTE 2 Cross-talk can be measured by substituting the receiver microphone with 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. The coupler and microphones should be positioned as during a calibration. Alternatively, cross-talk can be determined by setting the polarizing voltage to zero volts during a calibration. In both methods, frequency selective techniques are recommended.

7.3 Acoustic transfer impedance

7.3.1 General

Several factors influence the acoustic transfer impedance but the major source of uncertainty in its determination is often the microphone parameters, especially for small couplers.

7.3.2 Coupler properties

7.3.2.1 Coupler dimensions

The shape and dimensions of the coupler cavity shall be chosen in such a way that 6.4 is satisfied. As long as the greatest dimension of the coupler is small compared to the wavelength of sound in the gas, the sound pressure will be substantially uniform in the coupler and independent of the shape. At high frequencies and for large couplers, this requirement may be met by filling the cavity with helium or hydrogen.

The uncertainty on coupler dimensions affects the acoustic transfer impedance by different amounts that vary with frequency. It also influences the heat conduction and capillary tube corrections.

Examples of couplers are given in Annex C.

NOTE 1 Cylindrical couplers used in a frequency range where the dimensions are not small compared to the wavelength should be manufactured with the utmost care so that asymmetric sound fields are not excited.

NOTE 2 The influence on a microphone of an asymmetric sound pressure distribution in the coupler may be ascertained by changing the relative position of the coupler and microphones, for instance by incrementally rotating each microphone about its axis. If such a change affects the electrical transfer impedance, this effect should be taken into account when estimating the uncertainty.

NOTE 3 If the coupler is filled with a gas other than air, care should be taken to avoid leakage of the gas to the cavity behind the diaphragm of the microphone, by sealing the contacting surface with a thin layer of grease. If diffusion of the gas into the back cavity takes place, through the diaphragm or by other means, the microphone cannot be calibrated in this way as the microphone sensitivity is altered unpredictably.

7.3.2.2 Heat conduction and viscous losses

The correction for heat conduction and viscous losses shall be calculated from the equations given in Annex A for cylindrical couplers within the range of dimensions as described in Annex C. In the calculations the total coupler volume is understood as the sum of the geometrical volume of the coupler and the front cavity volumes of the coupled microphones. Similarly the total surface area is understood as the sum of the surface area of the coupler and the surface areas of the front cavities of the coupled microphones.

7.3.2.3 Capillary tube

If capillary tubes are used, the acoustic impedance shall be calculated from the equations given in Annex B. Long, narrow capillary tubes are recommended in order to minimize the effect of uncertainty on the dimensions of the tubes. The correction factor for capillary tubes is calculated from Equation (6) in 5.6.

7.3.2.4 Physical quantities

The acoustic transfer impedance depends on certain physical quantities describing the properties of the gas enclosed in the coupler. These quantities depend on environmental conditions such as static pressure, temperature and humidity. Values of the quantities and their dependence on environmental conditions are described in Annex F for humid air.

The resulting uncertainty on the quantities is a combination of the uncertainty on the equations in Annex F and the uncertainty on the measurement of the environmental conditions.

7.3.3 Microphone parameters

7.3.3.1 Front cavity

A laboratory standard microphone has a recessed cavity in front of the diaphragm.

In Equation (3), the volume of the front cavity forms a part of the total geometrical volume V of the coupler. In Equation (4), the depths of the front cavities similarly influence the length l_0 of the coupler. Because of production tolerances the volume and depth of the front cavity shall be determined individually for each microphone under test when calibrated in plane-wave couplers (see Annex E).

It will usually be found that the measured volume of the front cavity is different from the volume calculated from the cross-sectional area S_0 of the coupler and the cavity depth. This is because the diameter of the front cavity may differ slightly from the diameter of the coupler, the cavity may have a screw thread turned on its inner wall, which makes the cavity diameter somewhat ill-defined, and there may be an additional annular air space linked to the cavity around the edge of the microphone diaphragm. The excess volume of the cavity, defined as the difference between the actual front volume and the volume calculated from the cross-sectional area S_0 of the coupler and the front cavity depth, shall be considered an additional terminating impedance when using Equation (4). This may be done by setting $\underline{Z}_{a,1}$ and $\underline{Z}_{a,2}$ to be the impedance of the parallel connection of the microphone impedance and the impedance due to the excess volume.

NOTE 1 This excess volume can in some instances be negative.

NOTE 2 For front cavities with an inner thread, the larger surface of the thread results in increased heat conduction that affects the acoustic transfer impedance. If this effect is neglected when calculating the acoustic transfer impedance, the corresponding uncertainty component should be increased accordingly.

7.3.3.2 Acoustic impedance

The acoustic impedance of the microphone is a function of frequency and is determined mainly by the properties of the stretched diaphragm and the air enclosed in the cavity behind the diaphragm, and by the geometry of the backplate. To a first approximation the acoustic impedance can be expressed in terms of equivalent series-connected compliance, mass and resistance. This network can alternatively be described by compliance, resonance frequency and loss factor. Compliance is often given in terms of the low frequency value of the real part of the equivalent volume of the microphone (see 6.2.2 of IEC 61094-1:2000).

At very low frequencies, heat conduction in the cavity behind the diaphragm results in an increase of the equivalent volume of the microphone which for type LS1 microphones will be up to 5 %.

The acoustic impedance $\underline{Z}_a$ of each microphone forms an important part of the acoustic transfer impedance $\underline{Z}_{a,12}$ of the system and errors in the determination of $\underline{Z}_a$ influence the accuracy of the calibration in a complicated way, particularly at high frequencies.

Methods for determining the acoustic impedance are described in Annex E.

NOTE The accuracy to which the microphone parameters need to be measured in order to obtain a certain overall accuracy is related to the coupler used and the frequency.

7.3.3.3 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.

7.4 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, the sound field in the couplers, the movement of the microphone diaphragm and the geometry of the couplers when closed with the microphones. Examples where these assumptions may not be fully valid are:

– Small scale imperfections in the transmitter microphone may lead to asymmetric wave-motion which cannot be accounted for;

- Microphones may not be reciprocal. The effect of this can be minimized by combining only microphones of the same model;
- Radial wave-motion corrections, if applied, are based on idealized movements of the microphone diaphragms or on empirical data;
- The excess volume of the microphone front cavity, see 7.3.3.1, may not be dealt with correctly;
- A lumped parameter representation of the microphone acoustic impedance is only an approximation to the true impedance;
- Viscous losses along the coupler surface have been estimated by an approximate theory. In addition, the effect of viscous losses arising from an inner thread in the front cavity and surface roughness are not accounted for. This will affect the acoustic transfer impedance at high frequencies.

7.5 Uncertainty on pressure sensitivity level

The uncertainty on the pressure sensitivity level should be determined in accordance with ISO/IEC Guide 98-3. When reporting the results of a calibration the uncertainty, as function of frequency, shall be stated as the *expanded uncertainty of measurement* using a *coverage factor of $k = 2$*.

Due to the complexity of the final expression for the pressure sensitivity in Equation (7) 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 to 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 determining the microphone parameters and for coupling the microphones.

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 very small and the derived final expanded uncertainty of measurement would be essentially the same.

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
Frequency	7.2
Receiver ground shield	6.3
Transmitter ground shield	6.3; 7.2
Coupler properties	
Coupler length	7.3.2.1
Coupler diameter	7.3.2.1
Coupler volume	7.3.2.1; 7.3.2.2
Coupler surface area	7.3.2.1; 7.3.2.2
Unintentional coupler/microphone leakage	
Capillary tube dimensions	7.3.2.3
Static pressure	7.3.2.4
Temperature	7.3.2.4
Relative humidity	7.3.2.4
Microphone parameters	
Front cavity depth	7.3.3.1
Front cavity volume	7.3.3.1
Equivalent volume	7.3.3.2
Resonance frequency	7.3.3.2
Loss factor	7.3.3.2
Diaphragm compliance	7.3.3.2
Diaphragm mass	7.3.3.2
Diaphragm resistance	7.3.3.2
Additional heat conduction caused by front cavity thread	7.3.3.1
Polarizing voltage	6.5.3; 7.3.3.3
Imperfection of theory	
Heat conduction theory	Annex A
Adding of excess volume	7.3.3.1; 7.4
Viscosity losses	7.4
Radial wave-motion	6.4; 7.3.2.1, 7.4
Processing of results	
Rounding error	
Repeatability of measurements	
Static pressure corrections	6.5; Annex D
Temperature corrections	6.5; Annex D

Annex A
(normative)

Heat conduction and viscous losses in a closed cavity

A.1 General

In a closed coupler heat conduction between the air and the walls results in a gradual transition from adiabatic to isothermal conditions. The exact nature of this transition depends upon the frequency of the calibration and the dimensions of the coupler. In addition any sound particle velocity along the coupler surfaces will result in viscous losses. The resulting sound pressure generated by the transmitter microphone, i.e. a constant volume displacement source, will change accordingly. Two approaches for determining the resulting sound pressure are given:

– A low frequency solution based on heat conduction only and applicable to large-volume couplers and plane-wave couplers in the frequency range where wave-motion can be neglected.
– A broad-band solution applicable to plane-wave couplers only, including both heat conduction and viscous losses.

Plane-wave and large-volume couplers are described in Annex C.

A.2 Low frequency solution

At low frequencies, where the sound pressure can be assumed to be the same at all points in the coupler, the effect of heat conduction can be considered as an apparent increase in the coupler volume expressed by a complex correction factor $\underline{\Delta}_{\mathrm{H}}$ to the geometrical volume V in Equation (3).

The correction factor is given by:

$$\underline{\Delta}_{\mathrm{H}} = \frac{\kappa}{1+(\kappa-1)\underline{E}_{\mathrm{V}}} \tag{A.1}$$

where $\underline{E}_{\mathrm{V}}$ is the complex temperature transfer function defined as the ratio of the space average of the sinusoidal temperature variation associated with the sound pressure to the sinusoidal temperature variation that would be generated if the walls of the coupler were perfectly non-conducting. Tabulated values for $\underline{E}_{\mathrm{V}}$ are found in [A.1][2] as a function of parameters R and X, where:

R is the length to diameter ratio of the coupler;

$X = f\ell^2 /(\kappa\alpha_{\mathrm{t}})$;

f is the frequency in hertz (Hz);

ℓ is the volume to surface ratio of the coupler in metres (m);

α_{t} is the thermal diffusivity of the enclosed gas in square metres per second ($\mathrm{m}^2\cdot\mathrm{s}^{-1}$).

Tabulated values of $\underline{E}_{\mathrm{V}}$ for some values of R and X are given in Table A.1. The figures given are considered accurate to 0,000 01.

[2] Figures in square brackets refer to Clause A.4.

For finite cylindrical couplers within the range of dimensions as described in Annex C, the approximation described below on the complex quantity $\underline{E}_V$ results in errors less than 0,01 dB at frequencies above 20 Hz.

$$\underline{E}_V = 1 - \underline{S} + D_1 \underline{S}^2 + (3/4)\sqrt{\pi}\, D_2 \underline{S}^3 \quad \text{(A.2)}$$

where

$$\underline{S} = \left[-j \frac{1}{2\pi X} \right]^{1/2} = \frac{1-j}{2\sqrt{\pi X}}$$

$$D_1 = \frac{\pi R^2 + 8R}{\pi (2R+1)^2}$$

$$D_2 = \frac{R^3 - 6R^2}{3\sqrt{\pi}\,(2R+1)^3}$$

The modulus of $\underline{E}_V$, as calculated from Equation (A.2), is accurate to 0,01 % within the range 0,125 < R < 8 and for X > 5.

Table A.1 – Values for $\underline{E}_V$

Real part of E_V			X	Imaginary part of E_V		
***R* = 0,2**	***R* = 0,5**	***R* = 1**		***R* = 0,2**	***R* = 0,5**	***R* = 1**
0,721 27	0,719 96	0,720 03	1,0	0,240 38	0,223 23	0,221 46
0,800 92	0,801 22	0,801 28	2,0	0,177 22	0,169 86	0,168 85
0,837 27	0,837 51	0,837 54	3,0	0,148 18	0,143 04	0,142 36
0,859 07	0,859 20	0,859 22	4,0	0,130 03	0,126 14	0,125 63
0,873 93	0,874 02	0,874 03	5,0	0,117 32	0,114 21	0,113 80
0,893 43	0,893 48	0,893 49	7,0	0,100 30	0,098 07	0,097 77
0,910 82	0,910 86	0,910 86	10,0	0,084 77	0,083 21	0,083 00
0,936 93	0,936 94	0,936 94	20,0	0,060 86	0,060 07	0,059 97
0,948 50	0,948 51	0,948 51	30,0	0,050 02	0,049 50	0,049 42
0,955 40	0,955 41	0,955 41	40,0	0,043 49	0,043 10	0,043 04
0,963 58	0,963 59	0,963 59	60,0	0,035 68	0,035 41	0,035 38
0,968 46	0,968 46	0,968 46	80,0	0,030 98	0,030 78	0,030 76
0,971 79	0,971 79	0,971 79	100,0	0,027 76	0,027 61	0,027 58
0,980 05	0,980 05	0,980 05	200,0	0,019 72	0,019 64	0,019 63
0,985 90	0,985 90	0,985 90	400,0	0,013 99	0,013 95	0,013 95
0,990 03	0,990 03	0,990 03	800,0	0,009 92	0,009 90	0,009 89

The first two terms in Equation (A.2) constitute an approximation that may be used for couplers that are not right circular cylinders.

When calibrations are performed at frequencies below 20 Hz using the couplers described in Annex C, the full frequency domain solution given in [A.1] shall be used, or the corresponding uncertainty component shall be increased accordingly.

A.3 Broad-band solution

At high frequencies, where viscous losses are present in addition to the thermal losses, the effect of viscosity is to reduce the effective cross-sectional area of the coupler due to the boundary layer next to the surface and at the same time to increase the effective length of the coupler due to the reduced speed of sound. At low frequencies and for the couplers described in Annex C, the two effects compensate each other while the effect of heat conduction remains. The combined effect of heat conduction and viscous losses for sound propagation in cylindrical tubes has been derived in [A.2] based on Kirchhoff's theory.

The complex expressions for the propagation coefficient and the acoustic impedance of the coupler to be used in Equation (4) are:

$$\underline{\gamma} = \mathrm{j}\,\frac{\omega}{c}\left(1+\frac{1-\mathrm{j}}{\sqrt{2}}\,\frac{1}{a}\left(\sqrt{\frac{\eta}{\omega\rho}}+(\kappa-1)\sqrt{\frac{\alpha_{\mathrm{t}}}{\omega}}\right)\right) \tag{A.3}$$

$$\underline{Z}_{\mathrm{a},0} = \frac{\rho c}{S_0}\left(1+\frac{1-\mathrm{j}}{\sqrt{2}}\,\frac{1}{a}\left(\sqrt{\frac{\eta}{\omega\rho}}-(\kappa-1)\sqrt{\frac{\alpha_{\mathrm{t}}}{\omega}}\right)\right) \tag{A.4}$$

where

η is the viscosity of the gas in pascal-seconds (Pa·s);

a is the radius of the coupler in metres (m).

Values for c, η, ρ and α_{t} in humid air can be derived from equations given in Annex F.

In addition to the above losses at the cylindrical surface, heat conduction losses occur at the end surfaces. These losses can be dealt with by an admittance $1/\underline{Z}_{\mathrm{a,h}}$ added to each microphone admittance in Equation (4), see [A.3].

$$\frac{1}{\underline{Z}_{\mathrm{a,h}}} = \frac{S_0}{\rho c}\,\frac{1+\mathrm{j}}{\sqrt{2}}\,(\kappa-1)\,\frac{1}{c}\sqrt{\alpha_{\mathrm{t}}\,\omega} \tag{A.5}$$

If a microphone has an inner thread in the front cavity the additional heat conduction caused by the thread surface can be accounted for by adding the increased surface area of the thread to the cross-sectional area S_0 in Equation (A.5), see [A.4].

Equations (A.3) – (A.4) are valid for the frequency range given by $\omega\,\rho\,a^2 > 100\,\eta$. This corresponds to frequencies higher than 3 Hz and 12 Hz for plane-wave couplers as given in Table C.1 for type LS1P and LS2aP microphones respectively.

A.4 Reference documents

[A.1] GERBER, H. *Acoustic properties of fluid-filled chambers at infrasonic frequencies in the absence of convection,* Journal of Acoustical Society of America 36, 1964, pp. 1427-1434

[A.2] ZWIKKER, C. and KOSTEN, C.W. *Sound Absorbing Materials*, 1949. Elsevier, Amsterdam. Chapter II, § 4

[A.3] MORSE, P.M. and INGARD, K.U. *Theoretical Acoustics*, 1968. McGraw-Hill, New York. Chapters 6.4 and 9.2

[A.4] FREDERIKSEN, E. *Reduction of Heat Conduction Error in Microphone Pressure Reciprocity Calibration*. Brüel & Kjær Technical Review, 1, 2001. pp14-23

Annex B
(normative)

Acoustic impedance of a capillary tube

B.1 General

The acoustic input impedance $\underline{Z}_{a,C}$ of an open capillary tube is determined by means of the transmission line theory, see 5.6:

$$\underline{Z}_{a,C} = \underline{Z}_{a,t} \tanh \underline{\gamma} l_C \tag{B.1}$$

The relationship between $\underline{Z}_{a,t}$ and $\underline{\gamma}$ is given by (see [B.1] [3]):

$$\underline{\gamma}\underline{Z}_{a,t} = \mathrm{j}\frac{\omega\rho}{\pi a_t^2}\left[1 - \frac{2\mathrm{J}_1(\underline{k}a_t)}{\underline{k}a_t \mathrm{J}_0(\underline{k}a_t)}\right]^{-1} \tag{B.2}$$

and

$$\frac{\underline{\gamma}}{\underline{Z}_{a,t}} = \mathrm{j}\omega\frac{\pi a_t^2}{\rho c^2}\left[1 + \frac{2}{B\underline{k}a_t}(\kappa - 1)\frac{\mathrm{J}_1(B\underline{k}a_t)}{\mathrm{J}_0(B\underline{k}a_t)}\right] \tag{B.3}$$

where

$\mathrm{J}_0(\ )$, $\mathrm{J}_1(\ )$	are the cylindrical Bessel functions of first kind, zero and first order respectively of complex argument;
a_t	is the radius of the tube in metres (m);
$\underline{k} = (-\mathrm{j}\omega\rho/\eta)^{1/2}$	is the complex wavenumber in metres to the power minus one (m^{-1}), $B = (\eta / \rho\alpha_t)^{1/2}$;
η	is the viscosity of the gas in pascal-seconds (Pa·s);
ρ	is the density of the gas in kilogram per cubic metres ($\mathrm{kg \cdot m^{-3}}$);
α_t	is the thermal diffusivity of the gas in square metres per second ($\mathrm{m^2 \cdot s^{-1}}$).

The equations above shall be used to calculate the correction factor $\underline{\Delta}_C$ given in Equation (6).

Values for c, η, ρ and α_t in humid air can be derived from equations given in Annex F.

Alternatively, the capillary tube may be blocked along its full length by a suitable wire after assembling the coupler and microphones. In this case the correction factor $\underline{\Delta}_C$ equals 1.

The expressions given above are derived for an ideal circular tube and are sensitive to the fourth power of the radius of the tube. In practice, however, the inner sections of capillary tubes are not circular and a flow calibration of the tube may be necessary to determine the effective radius.

Tabulated values of the real and imaginary parts of $\underline{Z}_{a,C}$ at reference environmental conditions are given in Tables B.1 and B.2 for a typical range of parameters and frequency. The tables are intended to be used when testing a calculation program based upon Equations B.1 to B.3.

3 Figures in square brackets refer to Clause B.2.

In an actual calibration the equations given above should be used and the actual values of temperature, static pressure and relative humidity be applied.

Table B.1 – Real part of $\underline{Z}_{a,C}$ in gigapascal-seconds per cubic metre (GPa·s/m³)

Tube dimensions in mm

l_C = 50			Frequency	l_C = 100		
a_t = 0,1667	a_t = 0,20	a_t = 0,25	Hz	a_t = 0,1667	a_t = 0,20	a_t = 0,25
3,015	1,454	0,596	20	6,034	2,911	1,193
3,016	1,455	0,596	25	6,037	2,913	1,194
3,017	1,455	0,596	31,5	6,043	2,917	1,196
3,019	1,456	0,597	40	6,052	2,923	1,199
3,021	1,458	0,598	50	6,066	2,931	1,203
3,026	1,460	0,599	63	6,088	2,946	1,210
3,033	1,464	0,601	80	6,124	2,970	1,222
3,043	1,470	0,604	100	6,178	3,006	1,240
3,060	1,480	0,609	125	6,264	3,063	1,270
3,090	1,496	0,618	160	6,416	3,168	1,323
3,134	1,521	0,632	200	6,638	3,326	1,406
3,204	1,561	0,653	250	6,985	3,589	1,547
3,322	1,628	0,688	315	7,540	4,061	1,815
3,531	1,747	0,749	400	8,355	4,940	2,378
3,868	1,940	0,848	500	9,074	6,287	3,532
4,501	2,310	1,033	630	8,677	7,339	5,629
5,805	3,109	1,433	800	6,378	5,313	4,380
8,331	4,884	2,374	1 000	4,354	3,006	1,928
12,122	9,001	5,376	1 250	3,546	2,127	1,147
9,201	7,936	6,752	1 600	4,171	2,408	1,195
4,332	3,027	1,956	2 000	6,325	4,404	2,523
2,698	1,638	0,894	2 500	4,986	3,723	2,774
2,808	1,579	0,783	3 150	4,412	2,660	1,392
5,917	3,529	1,745	4 000	5,245	4,024	3,079
5,959	4,838	3,917	5 000	5,058	3,258	1,767
3,307	1,940	1,012	6 300	4,580	2,921	1,673
6,581	5,380	4,133	8 000	4,696	3,034	1,751
4,180	2,461	1,257	10 000	4,977	3,360	1,949
3,909	2,545	1,546	12 500	4,765	3,335	2,277
4,047	2,594	1,540	16 000	4,757	3,267	2,142
4,531	2,809	1,516	20 000	4,847	3,322	2.021

NOTE The values given in this table are valid at reference environmental conditions only (see Clause 4 and Table F.2).

Table B.2 – Imaginary part of $\underline{Z}_{a,C}$ in gigapascal-seconds per cubic metre (GPa·s/m^3)

Tube dimensions in mm

l_C = 50			Frequency	l_C = 100		
a_t = 0,1667	a_t = 0,20	a_t = 0,25	Hz	a_t = 0,1667	a_t = 0,20	a_t = 0,25
0,097	0,074	0,049	20	0,096	0,114	0,090
0,122	0,092	0,061	25	0,120	0,143	0,112
0,154	0,116	0,077	31,5	0,152	0,180	0,141
0,195	0,147	0,098	40	0,192	0,228	0,180
0,244	0,184	0,123	50	0,240	0,285	0,225
0,307	0,232	0,155	63	0,300	0,359	0,283
0,390	0,295	0,197	80	0,378	0,456	0,361
0,488	0,369	0,246	100	0,467	0,570	0,452
0,611	0,462	0,308	125	0,573	0,711	0,567
0,783	0,592	0,396	160	0,705	0,907	0,731
0,981	0,743	0,496	200	0,829	1,125	0,923
1,230	0,933	0,623	250	0,923	1,383	1,170
1,557	1,186	0,792	315	0,896	1,668	1,502
1,993	1,527	1,021	400	0,488	1,848	1,923
2,513	1,948	1,306	500	–0,676	1,418	2,203
3,192	2,533	1,711	630	–2,737	–0,771	0,932
3,992	3,354	2,325	800	–3,89	–3,149	–2,506
4,287	4,216	3,186	1 000	–3,030	–2,594	–2,129
1,347	3,171	3,733	1 250	–1,381	–1,156	–0,944
–5,328	–4,376	–3,270	1 600	0,430	0,455	0,280
–4,500	–3,769	–2,958	2 000	0,265	0,975	1,222
–1,998	–1,665	–1,281	2 500	–1,700	–1,549	–1,341
0,489	0,241	0,049	3 150	0,204	0,197	0,051
2,431	2,282	1,690	4 000	–1,070	–0,858	–0,516
–2,799	–2,427	–1,945	5 000	0,209	0,437	0,403
0,181	–0,041	–0,193	6 300	–0,071	–0,098	–0,222
–1,231	–0,589	0,227	8 000	–0,041	–0,029	–0,141
0,867	0,637	0,331	10 000	–0,053	0,152	0,209
–0,548	–0,705	–0,769	12 500	–0,281	–0,294	–0,276
–0,217	–0,406	–0,538	16 000	–0,175	–0,187	–0,226
0,426	0,341	0,134	20 000	–0,107	0,000	0,032
NOTE The values given in this table are valid at reference environmental conditions only (see Clause 4 and Table F.2).						

B.2 Reference document

[B.1] ZWIKKER, C. and KOSTEN, C.W. *Sound Absorbing Materials*, 1949. Elsevier, Amsterdam. Chapter II, § 2-3

Annex C
(informative)

Examples of cylindrical couplers for calibration of microphones

C.1 General

The coupler used in a reciprocity calibration should produce a uniform sound pressure distribution over the diaphragm of the transmitter and receiver microphones. It is particularly important that the pressure distribution over the diaphragm of the receiver microphone be as uniform as possible in order to be consistent with the definition of pressure sensitivity, see 3.4 of IEC 61094-1:2000. Due to radial wave-motion and asymmetry of diaphragm motion, this ideal condition can only be approximated. In order to extend the frequency range over which the coupler can be used (but only as regards the radial wave-motion), it is advantageous for the radial resonance frequency to be as high as possible, which calls for a coupler of small diameter. For practical reasons, the diameter of the coupler should be not less than the diameter of the diaphragms.

For a given coupler, however, it is possible to raise the resonance frequencies by introducing hydrogen or helium into the coupler instead of air (see 7.3.2). Theoretically it should then be possible to extend the upper usable frequency of the coupler by a factor equal to the ratio of the speed of sound in hydrogen (or helium) and air. It should, however, be noted that the wave velocity in the diaphragm of the microphones is almost independent of the gas in the coupler and thus not increased by the same factor as the speed of sound in the enclosed gas.

An important quantity in reciprocity calibration using a closed coupler is the acoustic transfer impedance $\underline{Z}_{a,12}$ of the total system (see 5.2 and 5.4) which shall be known with a high accuracy. At frequencies where the acoustic wavelength is great compared to the dimensions of the coupler, the sound pressure distribution is uniform in the whole coupler and $\underline{Z}_{a,12} = \underline{Z}'_{a,12}$ is determined by the effective volume of the coupler, i.e. the geometrical volume of the coupler including the front cavity volumes and the equivalent volumes of the microphones (see Equation (3)). At frequencies where the acoustic wavelength cannot be considered great compared to the dimensions of the coupler, wave motion will exist and it is difficult to obtain a theoretical expression for the transfer impedance unless the coupler has a very simple form. Equation (4) expresses the transfer impedance $\underline{Z}'_{a,12}$ of a cylindrical coupler with a diameter equal to the diameter of the diaphragms of the microphones assuming only plane waves in the coupler.

Methods for calculating the transfer impedance in other cases have been developed. In such cases, however, the wave motion correction should also be determined empirically.

Two groups of couplers are used in practice. Plane-wave couplers, where the diameter of the coupler is equal to the diameter of the diaphragms and large-volume couplers, where the coupler volume is very large compared to the microphone front volumes and equivalent volumes.

C.2 Plane-wave couplers

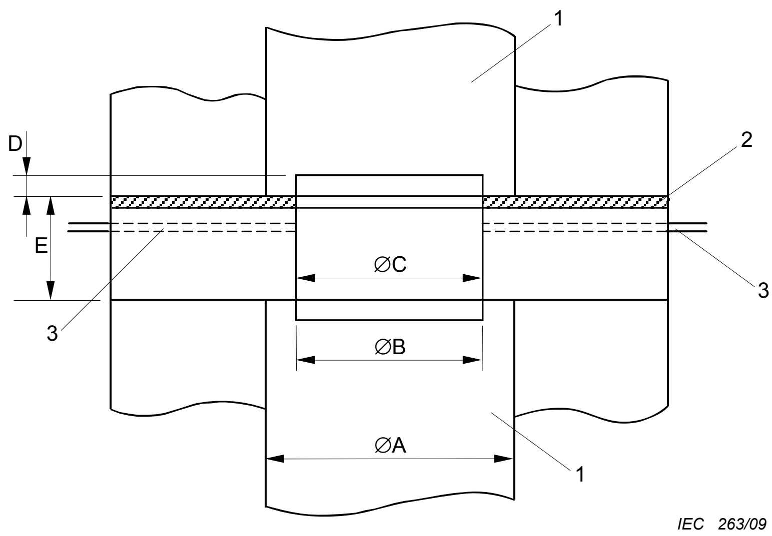
Plane-wave couplers have cavity diameters equal to the diameters of the microphone front cavities. The length of the coupler, i.e. the distance between the two diaphragms, should be long enough to ensure plane-wave transmission but not longer than a quarter of a wavelength. Coupler cavities having length to diameter ratios within the range of 0,5 to 0,75 are recommended. Such couplers will permit calibration of laboratory standard microphones of type LS1P up to about 10 kHz and type LS2P up to about 20 kHz when filled with air.

Analytical expressions can be derived for the influence of symmetric radial wave-motion for such couplers, under the assumption that the displacement function of the microphone diaphragms corresponds to idealized membrane vibrations. [C.2 - C.4][4]

Asymmetrical radial wave-motion will usually be present in the couplers. The lowest mode of these asymmetric modes occurs in plane wave couplers around 10,6 kHz and 21,2 kHz for types LS1 and LS2 microphones respectively.

Equation (4) should be used to calculate $\underline{Z}'_{a,12}$ and it is necessary to determine all the factors influencing $\underline{Z}_{a,12}$ (see 7.3), in particular the acoustic impedance of the microphones, with a high accuracy.

Recommended dimensions for plane-wave couplers are given in Table C.1 and Figure C.1.



Key

1 Microphone

2 Insulator

3 Capillary tubes

Figure C.1 – Mechanical configuration of plane-wave couplers

[4] Figures in square brackets refer to Clause C.4.

Table C.1 – Nominal dimensions for plane-wave couplers

Dimensions in mm

Dimensions	Laboratory standard microphones		
Symbol	Type LS1P	Type LS2aP	Type LS2bP
⌀A	23,77	13,2	12,15
⌀B	18,6	9,3	9,8
⌀C	18,6	9,3	9,8
D	1,95	0,5	0,7
E	3,5 – 9,5	3 – 7	3,5 – 6

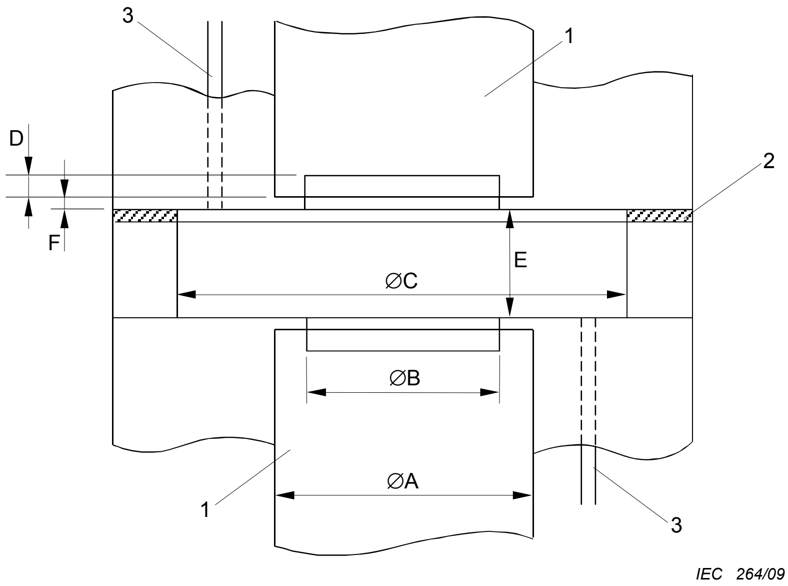
C.3 Large-volume couplers

Large-volume couplers have a larger volume than plane-wave couplers and the dimensions are so selected that the pressure decrease on the diaphragm due to the radial modes is partly cancelled by the pressure increase due to the longitudinal mode. The optimal length to diameter ratio is about 0,3 and depends upon the depth of the front cavities of the microphones.

Such couplers will permit the calibration of type LS1P up to about 2,5 kHz and of type LS2P microphones up to about 5 kHz when filled with air when using an empirically determined wave-motion correction. When a high accuracy is necessary, it is recommended to determine the wave-motion correction for the individual coupler used, since the mode pattern in the coupler is very sensitive to dimensions.

Equation (3) should be used to calculate $\underline{Z}'_{a,12}$ and it is only necessary to determine the sum of the front cavity volume and the equivalent volume of the microphones.

Recommended dimensions for large-volume couplers are given in Table C.2 and Figure C.2.



Key

1 Microphone

2 Insulator

3 Capillary tubes

Figure C.2 – Mechanical configuration of large-volume couplers

Table C.2 – Nominal dimensions and tolerances for large-volume couplers

Dimensions in mm

Dimensions	Laboratory standard microphones		
Symbol	**Type LS1P**	**Type LS2aP**	**Type LS2bP**
⌀A	23,77	13,2	12,15
⌀B	18,6	9,3	9,8
⌀C	42,88 ± 0,03	18,30 ± 0,03	18,30 ± 0,03
D	1,95	0,5	0,7
E	12,55 ± 0,03	3,50 ± 0,03	3,50 ± 0,03
F	0,80 ± 0,03	0,40 ± 0,03	0,40 ± 0,03

Table C.3 provides representative wave-motion corrections for the large-volume coupler used with type LS1P microphones. These corrections are to be added to the pressure sensitivity level determined when the coupler is filled with air, and may be applied in cases where it is not practical to determine the wave-motion corrections for the individual coupler and microphones used during a calibration. When the coupler is filled with hydrogen, the same corrections can be used provided the frequency scale is multiplied by a factor equal to the ratio of the speed of sound propagation in the existing hydrogen concentration to the corresponding speed in air.

Table C.3 – Experimentally determined wave-motion corrections for the air-filled large-volume coupler used with type LS1P microphones

Frequency Hz	**Correction** dB
≤ 800	0,000
1 000	-0,002
1 250	-0,013
1 600	-0,034
2 000	-0,060
2 500	-0,087

C.4 Reference documents

[C.1] MIURA, H. and MATSUI, E. *On the analysis of the wave motion in a coupler for the pressure calibration of laboratory standard microphones. J. Acoust. Soc. Japan* 30, 1974, pp. 639-646

[C.2] RASMUSSEN, K. *Radial wave-motion in cylindrical plane-wave couplers*. *Acta Acustica*, 1, 1993, pp 145-151

[C.3] GUIANVARC'H, C; DUROCHER, J. N.; BRUNEAU, A.; BRUNEAU, M. *Improved Formulation of the Acoustic Transfer Admittance of Cylindrical Cavities. Acta Acustica united with Acustica*, 92, 2006, pp 345-354

[C.4] KOSOBRODOV, R. and KUZNETSOV, S. *Acoustic Transfer Impedance of Plane-Wave Couplers, Acta Acustica united with Acustica*, 92, 2006, pp 513-520

Annex D
(informative)

Environmental influence on the sensitivity of microphones

D.1 General

This annex gives information on the influence of static pressure and temperature on the sensitivity of microphones.

D.2 Basic relations

The sensitivity of a condenser microphone is inversely proportional to the acoustic impedance of the microphone. In a lumped parameter representation, the impedance is given by the impedance of the diaphragm (due primarily to its mass and compliance) in series with the impedance of the enclosed air behind the diaphragm.

The impedance of the enclosed air is mainly determined by three parts:

– the thin air film between diaphragm and backplate, introducing dissipative loss and mass;
– the air in holes or slots in the backplate, introducing dissipative loss and mass;
– the air in the cavity behind the backplate, acting at low frequencies as a compliance but at high frequencies introducing additional resonances due to wave motion in the cavity.

Constructional details of the microphone determine the relative importance of the three parts.

The density and the viscosity of air are considered linear functions of temperature and/or static pressure. Consequently the resulting acoustic impedance of the microphone also depends upon the static pressure and the temperature. The static pressure and temperature coefficients of the microphone are then determined by the ratio of the acoustic impedance at reference conditions to the acoustic impedance at the relevant static pressure and temperature respectively.

D.3 Dependence on static pressure

Both the mass and the compliance of the enclosed air depend on static pressure, while the resistance can be considered independent of static pressure. The static pressure coefficient generally varies with frequency as shown in Figure D.1. For frequencies higher than about 0,5 f_0 (f_0 being the resonance frequency of the microphone), the frequency variation depends strongly upon the wave-motion in the cavity behind the backplate. In general, the pressure coefficient depends on constructional details in the shape of backplate and back volume, and the actual values may differ considerably for two microphones of different manufacture although the microphones may belong to the same generic type, e.g. LS1P. Consequently the pressure coefficients shown on Figure D.1 should not be applied to individual microphones.

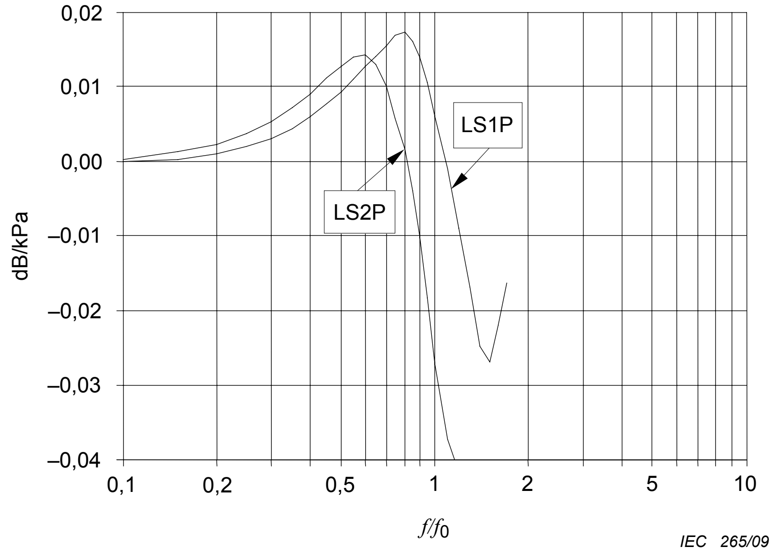


Figure D.1 – Examples of static pressure coefficient of LS1P and LS2P microphones relative to the low-frequency value as a function of relative frequency f/f_0

The low-frequency value (typically 250 Hz) of the static pressure coefficient is determined by the relationship between the compliances of the diaphragm itself and of the air enclosed behind the diaphragm. As the pressure sensitivity at low frequencies is determined by the resulting effective compliance of the diaphragm, the static pressure coefficient for individual samples of a given type of microphones is closely related to the individual sensitivity of the microphones at low frequencies.

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

At very low frequencies isothermal conditions will prevail in the cavity behind the diaphragm and thus the compliance of the cavity will increase. In addition, the influence of the static pressure equalization tube becomes significant. In the limit, the pressure sensitivity becomes independent of the static pressure. This effect becomes noticeable at frequencies below 2 Hz to 5 Hz for type LS1 and type LS2 microphones.

D.4 Dependence on temperature

Both the mass and the resistance of the enclosed air depend on temperature, while the compliance can be considered independent of temperature. The typical frequency dependence of the temperature coefficient is shown in Figure D.2.

In addition to the influence on the enclosed air, temperature variations also affect the mechanical parts of the microphone. The main effect generally will be a change in the tension of the diaphragm and thus a change in the compliance of the diaphragm and a change of the distance between diaphragm and backplate.

This results in a constant change in sensitivity in the stiffness controlled range and a slight change in resonance frequency.

The resulting temperature coefficient is a linear combination of the influence due to the variation of the impedance of the enclosed air and the influence due to the change of the mechanical tension.

The low-frequency value of the temperature coefficient generally lies in the range ± 0,005 dB/K for both LS1P and LS2P microphones. The temperature coefficient shown in Figure D.2 should not be applied to individual microphones.

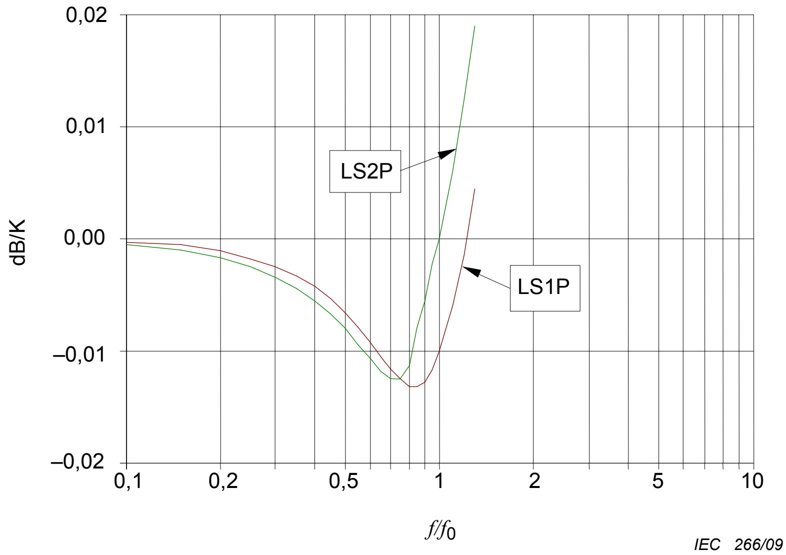


Figure D.2 – General frequency dependence of that part of the temperature coefficient for LS1P and LS2P microphones caused by the variation in the impedance of the enclosed air

D.5 Reference documents

[D.1] RASMUSSEN, K. *The static pressure and temperature coefficients of laboratory standard microphones. Metrologia*, 36, 1999, pp 256-273

[D.2] KOSOBRODOV, R and KUZNETSOV, S. *Static pressure coefficients of laboratory standard microphones in the frequency range 2 – 250 Hz. 11th ICSV*, 2004. St. Petersburg, Russia, pp 1441 – 1448

Annex E
(informative)

Methods for determining microphone parameters

E.1 General

This annex gives information on methods for determining the microphone parameters which influence the acoustic transfer impedance. The parameters are depth and volume of the front cavity, and acoustic impedance of the microphone.

E.2 Front cavity depth

The depth of the front cavity is determined by optical methods. A contour plot across a diameter of the diaphragm and outer rim can be obtained by an interferometric scanning technique, for example using a laser beam. Such measurements should be performed across at least two diameters perpendicular to each other. An alternative method is based on the use of a depth-focusing microscope to measure the distance between points on the top of the microphone rim and points on the microphone diaphragm. A number of readings distributed over the diaphragm and the top of the rim should be taken.

E.3 Front cavity volume and equivalent volume

The front cavity volume together with the equivalent volume is determined by acoustical methods. As far as practicable such determinations should be performed under reference environmental conditions.

The microphone under test is inserted into one port of a three-port coupler. Two other condenser microphones are fitted - one used as a transmitter and the other as a receiver. The electrical transfer impedance between the two microphones is measured, while the coupler is terminated in turn by the microphone under test and a number of cavities of known volume covering the range of actual microphone front cavity volumes. By interpolation between the measured transfer impedances, the volume of the front cavity together with the equivalent volume of the microphone is determined.

Alternatively the microphone under test may be used as the receiver microphone. This will generally result in a higher signal-to-noise ratio, when measuring the electrical transfer impedance. In this case a number of different couplers of known volume may be used or the changes of volume can be obtained by inserting a number of small, calibrated rings between the coupler and the microphone under test. The internal diameters of the rings should be equal to those of the microphone front cavity.

It is important to notice that, by both methods, the volume determined includes the equivalent volume of the acoustic impedance of the diaphragm (see IEC 61094-1).

The methods described above can be used only at low frequencies, where the coupler behaves as a simple compliance. Using the second method, it may be necessary to compensate for the differences in heat conduction and capillary tube corrections when the coupler volume is changed and the effects of degraded signal-to-noise ratio may need to be considered.

E.4 Acoustic impedance of the microphone

The acoustic impedance can be expressed directly as a complex impedance or as a complex equivalent volume, see IEC 61094-1. On the assumption that the microphone can be represented by an electro-acoustic two-port network as described by the reciprocity equations (1a), a lumped parameter representation is possible. Such lumped parameter representation will generally be of sufficient accuracy for the evaluation of $\underline{Z}_a$ (see 5.4) in the frequency range up to about 1,3 times the resonance frequency of the microphone.

The equivalent lumped parameters representing the acoustic impedance of the microphone may be the acoustic mass m_a, acoustic compliance c_a and acoustic resistance r_a, or the resonance frequency f_0, equivalent volume at low frequencies V_{eq}, and loss factor d of the diaphragm. The resonance frequency is the frequency at which the imaginary part of the acoustic impedance $\underline{Z}_a$ is zero. The asymptotic low frequency value of $\underline{Z}_a$ determines the compliance and the equivalent volume. The real part of $\underline{Z}_a$ at resonance determines the acoustic resistance and loss factor. The acoustic mass is calculated from the resonance frequency and the acoustic compliance. The relations between these parameters are:

$$(2\pi f_0)^2 = (m_a \cdot c_a)^{-1} \qquad V_{eq} = c_a \cdot \gamma_{ref} \cdot p_{s,ref} \qquad d = r_a / (2\pi f_0 \cdot m_a) = r_a \cdot 2\pi f_0 \cdot c_a$$

The acoustic impedance can be obtained by an indirect method based upon measurement of the electrical admittance $\underline{Y}$ of the microphone. During the electrical admittance measurements the microphone is acoustically terminated with a closed quarter-wavelength tube ($\underline{p}$ = 0 in Equation (1a)) and the acoustic impedance of the microphone is then calculated by iteration from:

$$\underline{Z}_a = \frac{\underline{Z}_{e,0} - \underline{Y}^{-1}}{\underline{M}_p^2} \tag{E.1}$$

$\underline{Z}_{e,0}$, the electrical impedance with the diaphragm blocked, may be determined from measurements made at frequencies sufficiently high (100 kHz to 200 kHz) that the diaphragm inertia effectively prevents motion ($\underline{q}$ = 0 in Equation (1a)).

The lumped parameters representing the acoustic impedance can also be determined by acoustical methods. At resonance the phase difference between the sound pressure acting on the diaphragm and the open-circuit voltage will be 90°. This frequency can be estimated by exciting the diaphragm with an electrostatic actuator while terminating the diaphragm with a closed quarter-wavelength tube. Under the same conditions the loss factor can be determined as the ratio of the sensitivities at resonance and at low frequencies.

A third method is based upon datafitting. As the sensitivity of the microphone does not depend on the coupler used during the calibration, calibrations can be performed using a number of plane-wave couplers, say four, of different length (see C.1). For each microphone the sum of front cavity volume and equivalent volume is corrected until the same sensitivity is obtained for all couplers in the low- and mid- frequency range. This is the same technique as described in E.3. Incorrect values of the three lumped parameters describing the acoustic impedance of the microphone result in systematic changes at high frequencies related to the length of the coupler. The nature of the changes is different for the three parameters. Losses have very little influence on the calculated sensitivities around the resonance frequency while a wrong resonance frequency shows a maximum influence. A wrong equivalent volume mainly influences the calculated responses above the resonance frequency. If the complex microphone sensitivity is determined, a 90° phase response is found at the resonance frequency.

Similarly the loss factor can be determined as the ratio of the sensitivities at resonance and the asymptotic value at low frequencies. However, the asymptotic value at low frequencies has to be estimated from the low frequency response ignoring the slight increase in the sensitivity at low frequencies caused by heat conduction in the back cavity of the microphone. It is essential for a successful data-fitting that a correction for radial wave-motion is applied and that other systematic errors like cross-talk have been eliminated before the data-fitting is performed.

Annex F
(informative)

Physical properties of humid air

F.1 General

Certain quantities, describing the properties of the enclosed gas in the coupler, enter the expressions for calculating the sensitivity of the microphones, see Equations (3) and (4) and Annexes A and B. These quantities depend on one or more of the measured environmental variables, static pressure, temperature and humidity.

A large number of investigations have been published in the literature where reference values for the quantities can be found for specified environmental conditions, i.e. for standard dry air at 0 °C and at a static pressure of 101,325 kPa. The calculation procedures for the properties of air under actual environmental conditions described in this annex, are based upon procedures recommended by other international bodies and the latest results reported in the literature that has found general international acceptance.

The equations 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 in percent (%);

and the quantities to be calculated are:

ρ density of air in kilograms per cubic metre ($kg{\cdot}m^{-3}$);

c speed of sound at actual frequency in metres per second ($m{\cdot}s^{-1}$);

κ ratio of specific heats;

η viscosity of air in pascal-seconds (Pa·s);

α_t thermal diffusivity of air in square metres per second ($m^2{\cdot}s^{-1}$).

The calculation procedures take into account that humid air is not an ideal gas and most of the quantities are described by a polynomial where the relevant constants are given in Table F.2. In order to derive the above-mentioned quantities some additional quantities and constants are used:

T = T_0+t, the thermodynamic temperature in kelvin (K);

T_0 = 273,15 K (0 °C);

T_{20} = 293,15 K (20 °C);

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

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

c_0 zero-frequency speed of sound in metres per second ($m{\cdot}s^{-1}$);

x_w mole fraction of water vapor in air;

x_c mole fraction of carbon dioxide in air;

$f(p_s,t)$ enhancement factor;

Z compressibility factor for humid air;

k_a thermal conductivity in $J{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}K^{-1}$;

C_p specific heat capacity at constant pressure in $J{\cdot}kg^{-1}{\cdot}K^{-1}$;

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

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

α_{vO} attenuation coefficient for vibrational relaxation in oxygen in metre to the power minus one (m^{-1});

α_{vN} attenuation coefficient for vibrational relaxation in nitrogen in metre to the power minus one (m^{-1}).

The equations used for the calculations are considered valid for environmental conditions within the ranges:

temperature	15 °C – 27 °C
static pressure	60 kPa – 110 kPa
relative humidity	10 % – 90 %

The uncertainties quoted on the equations are standard uncertainties.

F.2 Density of humid air

The density of humid air is calculated by the 'CIPM-2007 equation' as recommended by the 96th CIPM meeting, see [F.1][5]:

$$\rho = [3{,}483\,740 + 1{,}4446(x_c - 0{,}000\,4)] \times 10^{-3} \frac{p_s}{Z\,T}(1 - 0{,}378\,0\,x_w) \quad \text{(F.1)}$$

where

$$Z = 1 - \frac{p_s}{T}\left[a_0 + a_1 t + a_2 t^2 + (a_3 + a_4 t)x_w + (a_5 + a_6 t)x_w^2\right] + \frac{p_s^2}{T^2}(a_7 + a_8 x_w^2)$$

$$x_w = \frac{H}{100}\frac{p_{sv}(t)}{p_s} f(p_s, t)$$

$$p_{sv}(t) = \exp(a_0 T^2 + a_1 T + a_2 + a_3 T^{-1})$$

$$f(p_s, t) = a_0 + a_1 p_s + a_2 t^2$$

The composition of standard air is based upon a carbon dioxide mole fraction of 0,000 314. It is generally accepted that under laboratory conditions a higher value is found and in the absence of actual measurements a value of x_c = 0,000 4 is recommended.

The relative uncertainty on the equation itself is estimated to 22×10^{-6}.

F.3 Speed of sound in air

In the absence of dispersion, the speed of sound is given by the zero-frequency speed of sound, see [F.2]:

$$\begin{aligned} c_0 &= a_0 + a_1 t + a_2 t^2 + (a_3 + a_4 t + a_5 t^2)x_w + (a_6 + a_7 t + a_8 t^2)p_s \\ &+ (a_9 + a_{10} t + a_{11} t^2)x_c + a_{12} x_w^2 + a_{13} p_s^2 + a_{14} x_c^2 + a_{15} x_w p_s x_c \end{aligned} \quad \text{(F.2)}$$

The relative uncertainty on the zero-frequency speed of sound is estimated to 3×10^{-4}.

---

5 Figures in square brackets refer to Clause F.8.

NOTE The speed of sound depends slightly on frequency due to dispersion as a result of relaxation effects among the constituents of air. In the frequency range relevant for this standard, the influence of dispersion on the speed of sound is less than the relative uncertainty on the zero-frequency speed of sound given by (F.2). The speed of sound at the actual measurement frequency can be calculated from the expression, see [F.4]:

$$\frac{1}{c}=\frac{1}{c_0}-\sum_n \frac{\alpha_{\mathrm{v}n}}{2\pi f_{\mathrm{v}n}} ,$$

where α_{v} and f_{v} are the attenuation coefficient and relaxation frequency, respectively, for vibrational relaxation effects. n denotes the component (nitrogen or oxygen) of air. These values are calculated from [F.6].

The equation may be rewritten into a more convenient form:

$$c=c_0\left[1+\sum_n \frac{c\cdot\alpha_{\mathrm{v}n}}{2\pi f_{\mathrm{v}n}}\right],$$

where the product $c\cdot\alpha_{\mathrm{vn}}$ is independent of the speed of sound, c.

F.4 Ratio of specific heats of air

The ratio of specific heats is calculated from, see [F.2]:

$$\begin{aligned}\kappa &= a_0+a_1t+a_2t^2+(a_3+a_4t+a_5t^2)x_{\mathrm{w}}+(a_6+a_7t+a_8t^2)p_{\mathrm{s}} \\ &+(a_9+a_{10}t+a_{11}t^2)x_{\mathrm{c}}+a_{12}x_{\mathrm{w}}^2+a_{13}p_{\mathrm{s}}^2+a_{14}x_{\mathrm{c}}^2+a_{15}x_{\mathrm{w}}p_{\mathrm{s}}x_{\mathrm{c}}\end{aligned} \tag{F.3}$$

The relative uncertainty on the ratio of specific heats is estimated to $3{,}2\times10^{-4}$.

F.5 Viscosity of air

The viscosity of air is calculated from, see [F.5]:

$$\eta=(a_0+a_1T+(a_2+a_3T)x_{\mathrm{w}}+a_4T^2+a_5x_{\mathrm{w}}^2)\times10^{-8} \tag{F.4}$$

F.6 Thermal diffusivity of air

The basic definition of the thermal diffusivity of air is:

$$\alpha_{\mathrm{t}}=\frac{k_{\mathrm{a}}}{\rho C_p} \tag{F.5}$$

where

$$k_{\mathrm{a}}=4186{,}8\times\left[a_0+a_1T+a_2T^2+(a_3+a_4T)x_{\mathrm{w}}\right]\times10^{-8}$$

$$C_p=4186{,}8\times\left[a_0+a_1T+a_2T^2+a_3T^3+(a_4+a_5T+a_6T^2)x_{\mathrm{w}}+(a_7+a_8T+a_9T^2)x_{\mathrm{w}}^2\right]$$

F.7 Examples

Table F.1 gives the values of the quantities given in Clauses F.1 to F.5 for two sets of environmental variables. The values in the table are intended for testing programs used to calculate these quantities and thus the figures are shown with more decimals than relevant in practice. Table F.2 lists the various coefficients necessary to calculate these quantities.

Table F.1 – Calculated values of the quantities in Clauses F.1 to F.5 for two sets of environmental conditions

Environmental conditions	Density of air ρ kg·m^{-3}	Speed of sound c_0 m·s^{-1}	Ratio of specific heats κ	Viscosity of air η Pa·s	Thermal diffusivity of air α_t m^2·s^{-1}
t = 23 °C p_s = 101 325 Pa H = 50 %	1,186 084 8	345,866 52	1,400 757 3	1,826 566×10^{-5}	2,115 317×10^{-5}
t = 20 °C p_s = 80 000 Pa H = 65 %	0,944 158 9	344,382 67	1,400 026 6	1,811 295×10^{-5}	2,627 024×10^{-5}

Table F.2 – Coefficients used in the equations for humid air properties

Coefficients	Saturation water vapor pressure	Enhancement factor	Compressibility factor	Zero-frequency speed of sound	Ratio of specific heats	Viscosity	Thermal conductivity	Specific heat capacity at constant pressure
Symbol	p_{sv}	$f(p_s,t)$	Z	c_0	κ	η	k_a	C_p
a_0	$1,237\,884\,7\times10^{-5}$	1,000 62	$1,581\,23\times10^{-6}$	331,502 4	1,400 822	84,986	60,054	0,251 625
a_1	$-1,912\,131\,6\times10^{-2}$	$3,14\times10^{-8}$	$-2,933\,1\times10^{-8}$	0,603 055	$-1,75\times10^{-5}$	7,0	1,846	$-9,252\,5\times10^{-5}$
a_2	33,937 110 47	$5,6\times10^{-7}$	$1,104\,3\times10^{-10}$	–0,000 528	$-1,73\times10^{-7}$	113,157	$2,06\times10^{-6}$	$2,133\,4\times10^{-7}$
a_3	$-6,343\,164\,5\times10^{3}$		$5,707\times10^{-6}$	51,471 935	–0,087 362 9	–1	40	$-1,004\,3\times10^{-10}$
a_4			$-2,051\times10^{-8}$	0,149 5874	–0,000 166 5	$-3,750\,1\times10^{-3}$	$-1,775\times10^{-4}$	0,124 77
a_5			$1,989\,8\times10^{-4}$	–0,000 782	$-3,26\times10^{-6}$	–100,015		$-2,283\times10^{-5}$
a_6			$-2,376\times10^{-6}$	$-1,82\times10^{-7}$	$2,047\times10^{-8}$			$1,267\times10^{-7}$
a_7			$1,83\times10^{-11}$	$3,73\times10^{-8}$	$-1,26\times10^{-10}$			0,011 16
a_8			$-0,765\times10^{-8}$	$-2,93\times10^{-10}$	$5,939\times10^{-14}$			$4,61\times10^{-6}$
a_9				–85,209 31	–0,119 971 7			$1,74\times10^{-8}$
a_{10}				–0,228 525	–0,000 869 3			
a_{11}				$5,91\times10^{-5}$	$1,979\times10^{-6}$			
a_{12}				–2,835 149	–0,011 04			
a_{13}				$-2,15\times10^{-13}$	$-3,478\times10^{-16}$			
a_{14}				29,179 762	0,045 061 6			
a_{15}				0,000 486	$1,82\times10^{-6}$			

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