IEC 61094-3

Edition 2.0 2016-06

INTERNATIONAL STANDARD

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colour inside

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

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 61094-3:2016-06(en-fr)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 17.140.50; 33.160.50

ISBN 978-2-8322-3478-5

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CONTENTS

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ELECTROACOUSTICS – MEASUREMENT MICROPHONES –

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

FOREWORD

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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- withdrawn,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.

The contents of the Corrigendum 1 of December 2016 have been included in this copy.

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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:

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

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 ($V{\cdot}s{\cdot}m^{-3}$), $\underline{M}_p$ 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:

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

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

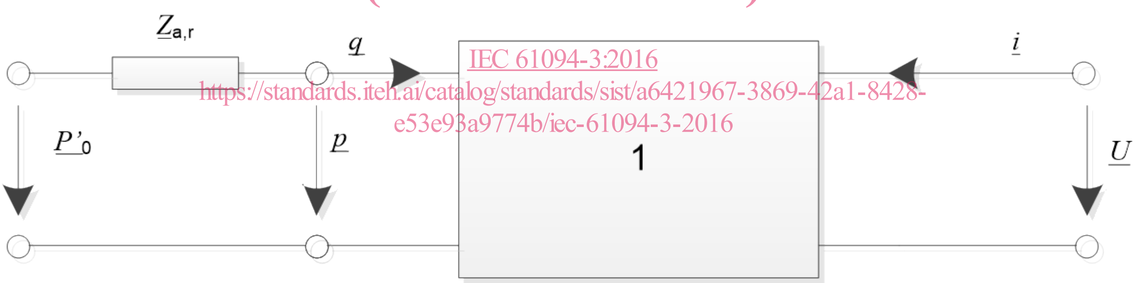
The insert voltage technique is used to determine the open-circuit voltage of a microphone when it is electrically loaded.

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:

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

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

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

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:

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

so that:

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

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 $\underline{p}_{0}$ 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:

$$\underline{M}_{\mathrm{f,1}} = \left(\underline{r}_{12} \frac{2 d_{12}}{\rho f} \underline{Z}_{\mathrm{e,12}} \, \mathrm{e}^{\mathrm{j} k d_{12}} \, \mathrm{e}^{\alpha d_{\mathrm{m12}}} \right)^{1/2} \tag{9}$$

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.