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BSI Standards Publication

Electroacoustics — Hearing aids — Method for measuring electroacoustic performance up to 16 kHz

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National foreword

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TECHNICAL SPECIFICATION

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Electroacoustics – Hearing aids – Method for measuring electroacoustic performance up to 16 kHz

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROACOUSTICS – HEARING AIDS – METHOD FOR MEASURING ELECTROACOUSTIC PERFORMANCE UP TO 16 kHz

FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

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

IEC TS 62886, which is a Technical Specification, has been prepared by IEC technical committee 29: Electroacoustics.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
29/897/DTS	29/902A/RVC

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

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

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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

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INTRODUCTION

Advancement in hearing aid design makes it possible to increase the bandwidth of hearing aids up to 16 kHz. Accordingly, there is a need for an accurate and yet robust measurement method for the transducer (receiver, earphone) designer, the hearing aid designer, and the fitter of hearing aids.

The 2 cm^3 coupler as described in IEC 60318-5 is only suitable for measurements up to 8 kHz. The limitation is caused by unfavourable acoustic modes of the coupler.

The occluded-ear simulator as described in IEC 60318-4 simulates the average human external ear up to 8 kHz, and can be used as a test coupler up to 16 kHz. The occluded ear-simulator is designed for a specific insertion depth of the earmould, which is associated with a half-wavelength $\lambda/2$ resonance at about 13,5 kHz. This half-wavelength resonance degrades the reproducibility of measurement results in that frequency range and harmonic distortion measurements made at corresponding multiples of the resonance frequency. Also, this resonance represents a complex load to the hearing aid transducer, which makes it more difficult to differentiate between transducer and load related effects.

The effective internal volume of the coupler described in this Technical Specification is 0,4 cm^3, which is small enough not to produce any resonance in the frequency range below 16 kHz. The frequency response of the magnitude of acoustic impedance follows a pattern of a capacitive load up to about 30 kHz. With a sufficiently high source impedance and a sufficiently small coupling volume, the 0,4 cm^3 coupler produces an approximately 14 dB higher output at 1 kHz in comparison to data obtained with the 2 cm^3 coupler.

The coupler described in this document will allow the characterisation of hearing aids and transducers, including the verification of simulation models, up to 16 kHz.

0,4 cm^3 is also approximately the residual volume of the ear canal when fitted with a CIC hearing aid (completely-in-the-canal) hearing aid, making this coupler particularly useful for this application.

In combination with an appropriate real-ear probe microphone measurement, the 0,4 cm^3 coupler will enable the derivation of real-ear to coupler difference (RECD) up to 16 kHz.

ELECTROACOUSTICS – HEARING AIDS – METHOD FOR MEASURING ELECTROACOUSTIC PERFORMANCE UP TO 16 kHz

1 Scope

IEC TS 62886, which is a Technical Specification, describes a coupler and measurement methods to characterise the electroacoustic performance of hearing aids and insert earphones primarily in the range of 8 kHz to 16 kHz.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60118-0, *Electroacoustics – Hearing aids – Part 0: Measurement of the performance characteristics of hearing aids*

IEC 60318-4, *Electroacoustics – Simulators of human head and ear – Part 4: Occluded-ear simulator for the measurement of earphones coupled to the ear by means of ear inserts*

IEC 60318-5, *Electroacoustics – Simulators of human head and ear – Part 5: 2 cm^3 coupler for the measurement of hearing aids and earphones coupled to the ear by means of ear inserts*

IEC 61094-4, *Measurement microphones – Part 4: Specifications for working standard microphones*

IEC 60263, *Scales and sizes for plotting frequency characteristics and polar diagrams*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
reference cavity
simple cylindrical cavity with the same nominal diameter and height as the coupler under test, establishing a volume that can be measured using precision dimensional metrology

Note 1 to entry: In the context of this document, the reference cavity is 400 mm^3 ± 3 mm^3, with a diameter of 9,45 mm ± 0,02 mm and a height of 5,70 mm ± 0,02 mm.

3.1.2
effective coupler volume
adjusted volume of the coupler under test that causes the measured sound pressure level in the coupler under test to equal the measured sound pressure level in the reference cavity

3.1.3
coupler volume ratio
20 times the logarithmic ratio to the base of 10 of the effective coupler volumes of a 2 cm^3 and 0,4 cm^3 coupler ($20 \lg \frac{V_{2\ \mathrm{cm}^3}}{V_{0,4\ \mathrm{cm}^3}}$ dB)

Note 1 to entry: The coupler volume ratio is expressed in dB.

Note 2 to entry: The coupler volume ratio can vary between 13,46 dB and 14,50 dB since the effective coupler volume of the 2 cm^3 coupler (according to IEC 60318-5) is defined as 2 000 mm^3 ± 70 mm^3 and the effective coupler volume of the 0,4 cm^3 coupler is defined as 400 mm^3 ± 10 mm^3 (see 4.2.2).

3.1.4
coupler level difference
difference between the sound pressure levels in the 0,4 cm^3 coupler and the 2 cm^3 coupler produced by the same sound source

Note 1 to entry: The coupler level difference includes the influence of the impedance of the sound source. For finite source impedance, the coupler level difference will be less than the coupler volume ratio.

3.1.5
effective length of coupling tubing
length of the acoustic coupling tubing that extends from the output of the receiver or BTE hearing aid ear hook to the coupler reference plane

Note 1 to entry: The actual length of tubing used may deviate from the effective length of coupling tubing, for example, a) the overlap resulting from the connection to the ear hook or hearing aid receiver may increase the actual length of tubing used, whereas (b) connection to the nipple of the coupling plate or earmould simulator, which is considered part of the effective length of coupling tubing, may reduce the actual length of tubing used accordingly. See Figure 2, Figure 5 and Figure 6.

3.2 Abbreviated terms

CIC	completely-in-the-canal
ITC	in-the-canal
IIC	invisible-in-the-canal
ITE	in-the-ear
BTE	behind-the-ear
RIC	receiver-in-the canal
RECD	real-ear to coupler difference
SPL	sound pressure level

4 Mechanical design of the 0,4 cm^3 coupler

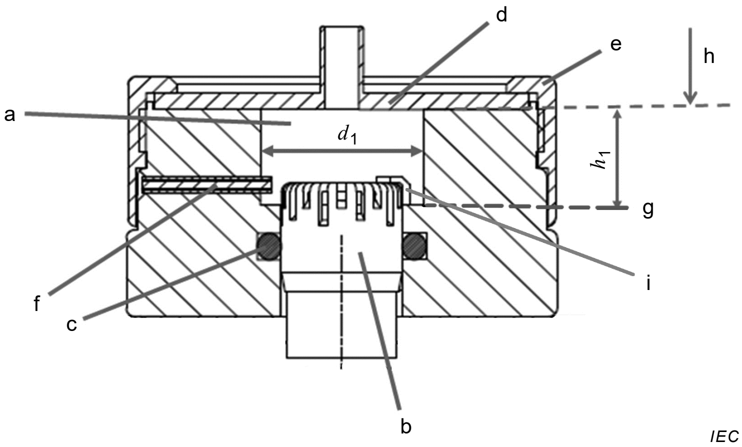
4.1 General

The coupler consists essentially of a cylindrical cavity whose effective volume is nominally 400 mm^3. The base of the cylindrical cavity contains the diaphragm of a microphone, or a microphone with an adaptor. A protection grid may or may not be fitted. The microphone measures the sound pressure level (SPL) in the coupler. The coupler shall be constructed of hard, dimensionally stable, non-porous and non-magnetic material. The general construction of the coupler and mounting of the microphone shall aim to minimise the response of the microphone to vibration (for example from an earphone) or to extraneous sound outside the cavity.

The external diameter of the coupler should be kept as small as possible in order to minimise diffraction errors which might affect the measurements when the coupler has to be placed in a sound field.

Where tolerances are specified in this document, these shall be reduced by an amount equal to the actual expanded measurement uncertainty of the test laboratory before deciding if a device conforms to the stated requirement.

Figure 1 shows the mechanical design of the coupler.



Key

d_1 Cavity diameter

h_1 Cavity height

a Cylindrical cavity

b Measuring microphone with protection grid

c O-ring or other means of airtight sealing

d Coupling plate (removable)

e Coupling plate lock bushing

f Static pressure equalization vent

g Cavity base; plane of microphone diaphragm

h Coupler reference plane

i Microphone insertion stop feature

Figure 1 – Mechanical design of the 0,4 cm^3 coupler, shown with removable coupling plate with a nipple for the attachment of coupling tubing

4.2 Cavity dimensions

4.2.1 Critical dimensions

The critical dimensions of the coupler are those which determine the shape and the volume of the cavity terminated by a measurement microphone, and the static pressure equalisation vent.

4.2.2 Effective coupler volume

The effective coupler volume shall be 400 mm^3 ± 10 mm^3.

The contribution of any front cavity and of the finite diaphragm impedance associated with the measurement microphone shall be included in the effective volume of the coupler. Therefore, the height of the cylindrical cavity should be designed such that the effective volume of the coupler conforms to the requirement for all microphone models intended for use with the coupler.

4.2.3 Diameter of the coupler cavity

The diameter d_1 of the cylindrical coupler cavity shall be 9,45 mm ± 0,05 mm.

4.3 Verification procedure of the effective coupler volume

4.3.1 General

The verification of the effective coupler volume (see 3.1.2) by acoustical means is performed by comparing the sound pressure in the coupler – which includes the coupler microphone with protection grid, the static pressure equalisation vent, microphone insertion stop if fitted and any other feature affecting the effective volume – with the sound pressure produced in a reference cavity (see 3.1.1).

4.3.2 Test set-up

The coupling plate for this test includes a source and a control microphone. This assembly can be attached to the reference cavity and the coupler under test. The control microphone measures the sound pressure in the reference cavity and in the coupler under test. The sound source input signal shall be the same for both measurements.

NOTE If both measurements are performed immediately one after another in a stable environment, effects related to heat conduction into the cavity walls will be essentially the same for both tests.

4.3.3 Effective volume of the coupler under test

During the sound pressure measurements made in the coupler under test and in the reference cavity, the effective volume of the coupler under test and the effective volume of the reference cavity will be increased by the effective volume V_s of the sound source.

Measurement in reference cavity: $p_{ref} \sim 1/(V_{ref} + V_s)$

Measurement in coupler under test: $p_{coupler} \sim 1/(V_{coupler} + V_s)$

Assuming constant air temperature and using Boyle's law:

$$p_{ref}/(V_{ref} + V_s) = p_{coupler}/(V_{coupler} + V_s)$$

$$V_{coupler} = \left(\frac{P_{ref}}{P_{coupler}}\right) V_{ref} + \left(\frac{P_{ref}}{P_{coupler}}\right) V_s - V_s$$

where

V_{ref}	is the volume of reference cavity
$V_{coupler}$	is the volume of the coupler under test
V_s	is the effective volume of the sound source which is the combined volumes of the sound source and control microphone
p_{ref}	is the sound pressure in the reference cavity
$p_{coupler}$	is the sound pressure in the coupler under test

V_s cancels out, if $p_{coupler}$ equals p_{ref}.

Subsequently, $V_{coupler}$ equals V_{ref}.

4.4 Measuring microphone

4.4.1 General

Unless a qualified alternative microphone is used (see 4.4.3), the internal shape of the base of the coupler shall enable a WS3P microphone as specified in IEC 61094-4, with protection grid, to be fitted into the base in such a way that the microphone diaphragm is flush with the interior surface of the coupler base.

4.4.2 Preferred microphone

The preferred microphone is a WS3P 6,35 mm pressure microphone as specified in IEC 61094-4. Alternatively, other microphones, including those with smaller dimensions, may be used, provided they fulfil the requirements of 4.4.3.

NOTE The equivalent volume of a WS3P microphone is approximately 0,25 mm^3.

4.4.3 Alternative microphones

The overall pressure sensitivity level of any alternative microphone and the associated measuring system shall be known by calibration with an expanded measurement uncertainty ($k = 2$) of no more than 0,2 dB over the frequency range of 100 Hz to 8 kHz (when measurements are being made over this range) and no more than 0,4 dB over the frequency range of 8 kHz to 16 kHz.

If a microphone, for which the diameter of the movable part of the diaphragm is less than the diameter of the cavity of the coupler is used, the microphone, with or without protection grid, shall be located concentrically in the base of the coupler cavity. The effective coupler volume shall be preserved. The use of an alternative microphone and the associated measurement uncertainty of the pressure sensitivity level shall be stated by the user.

Measurements performed with an alternative microphone and a WS3P microphone shall not differ by more than 0,3 dB for frequencies up to 16 kHz.

4.5 Static pressure equalisation vent

Any change in the static pressure within the cavity caused by coupling the hearing aid or the earphone to the coupler and microphone shall decay toward the static ambient pressure with a time constant of less than 1,5 s. If this necessitates the introduction of a controlled leak in the coupler, it shall have the following characteristics:

a) it shall not alter the cavity volume by more than 4 mm^3;
b) it shall attenuate external sound reaching the cavity, with the coupling plate aperture sealed, by at least 16 dB at 125 Hz, increasing by 6 dB per octave for increasing frequency.

NOTE 1 Equalisation can be realised, for example, by a capillary tube.

NOTE 2 In the time domain, 4.5 b) is equivalent to having the equalisation allow air movement between the interior and the exterior of the cavity at a rate such that a pressure change in the interior of the cavity with respect to the exterior will equalise to 0,368 of the initial difference (one time constant) in less than 1,5 s.

5 Calibration

5.1 Reference environmental conditions

To ensure proper calibration of the microphone system the following environmental condition shall be met:

Reference ambient pressure: 101,325 kPa ± 3 kPa
Reference temperature: 23 °C ± 3 °C

Reference relative humidity 50 % ± 20 %

If it is not possible to fulfil these requirements, the actual condition shall be stated.

5.2 Calibration procedure

The manufacturer shall describe a calibration method for the microphone system used in the coupler in the instruction manual.

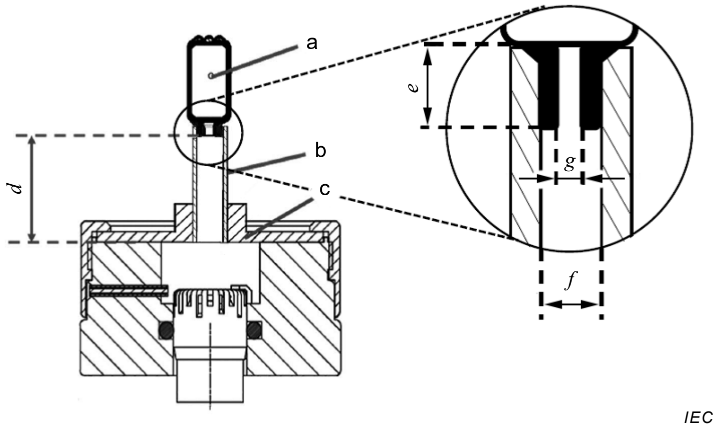
6 Coupling of receivers and hearing aids to the coupler

6.1 Coupling to a hearing aid receiver by means of tubing

Figure 2 describes the coupling to a hearing aid receiver. A bore diameter in the coupling plate can be used which fits the coupling tubing external diameter. The tubing is glued into the coupling plate for proper fixation and acoustic seal. The end of the tubing should be flush with the lower face of the coupling plate.

For standardised measurements on hearing aid receivers, a tubing with an internal diameter of 1 mm and an effective tubing length of 5 mm shall be used.

NOTE For more reliable sealing of the coupling tubing to the coupling plate, the thickness of the coupling plate can be increased in the centre portion.



Key

a Hearing aid receiver

b Coupling tubing

c Coupling plate with central bore corresponding to the external diameter of coupling tubing

d Effective length of coupling tubing

e Length of receiver connection port

f Internal diameter of coupling tubing

g Effective diameter of receiver connection port

Figure 2 – Coupling to a hearing aid receiver by means of coupling tubing

6.2 Coupling to a hearing aid embedded in or connected to an earmould

Subclause 6.2 is applicable to any style of hearing aid embedded in or attached to an earmould.

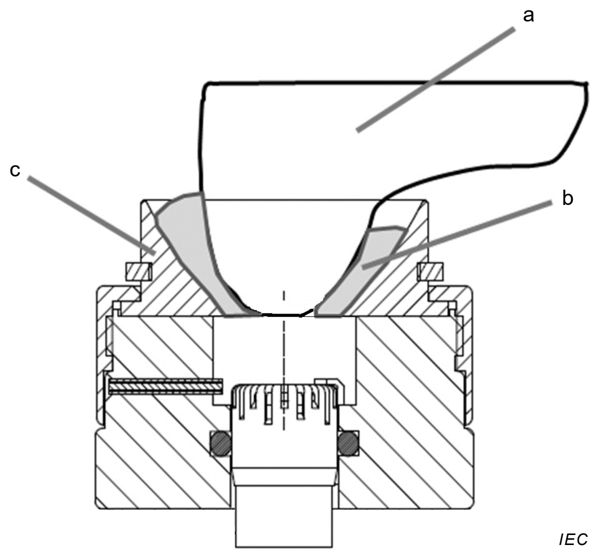
Examples of hearing aids fully embedded in the earmould are ITE (in-the-ear), ITC (in-the-canal), CIC (completely-in-the-canal), IIC (invisible-in-the-canal) hearing aids.

An example of a partially embedded hearing aid is the receiver-in-the-canal (RIC) hearing aid.

Examples of hearing aids attached to an earmould are behind-the-ear (BTE) hearing aids either coupled with standard coupling tubing or thin tubing.

The coupling concept is illustrated in Figure 3 where it is shown with an ITE hearing aid. The coupling is performed by attaching the ITE hearing aid by means of a sealant to the concave shaped ITE hearing aid mounting fixture. Care should be taken to avoid any gaps or slit leakages. Any vents in the hearing aid shall be sealed at the coupler side of the vent flush with the coupler reference plane. Any seal should not protrude into the coupler cavity. The end of the ITE hearing aid sound channel should be flush with the coupler reference plane. The coupling plate is removable from the 0,4 cm^3 coupler. This allows the inspection of the seal quality and the position of the opening of the sound tube that will face the inside volume of the coupler.

NOTE Due to the smaller volume, the 0,4 cm^3 coupler is more sensitive to gaps or slit leakages than the 2 cm^3 coupler.



Key

a ITE hearing aid

b Sealant to seal ITE hearing aid to mounting fixture

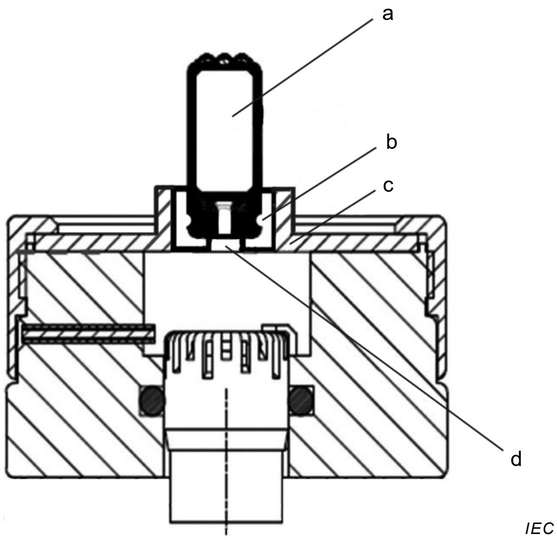
c ITE hearing aid mounting fixture

Figure 3 – Coupling to an ITE hearing aid

6.3 Coupling to a receiver in the canal (RIC hearing aid)

Figure 4 shows the coupling to a receiver in the canal (RIC hearing aid) to the 0,4 cm^3 coupler. This can be used as an alternative to 6.2 provided that a coupling adapter is available. The coupling adapter is considered a part of the receiver system, and therefore its lower face shall be aligned with the coupler reference plane.

If the receiver is attached to an earmould, then coupling as described in Figure 3 shall be used.



Key

a Receiver in the canal (RIC hearing aid)

b RIC hearing aid specific coupling adaptor

c Coupling plate

d Bore in RIC hearing aid specific coupling adaptor

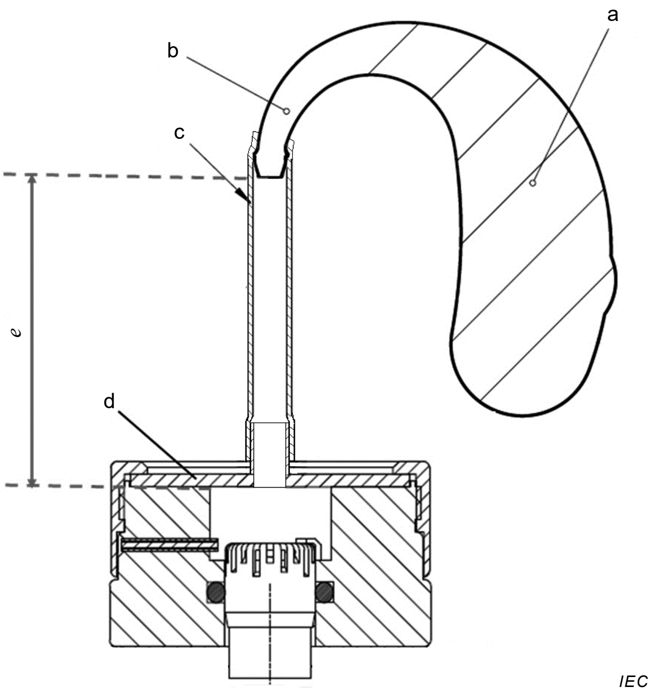
Figure 4 – Coupling to a receiver in the canal (RIC hearing aid)

6.4 Coupling to a BTE hearing aid with 2 mm continuous internal diameter tubing

Figure 5 shows the coupling to a BTE hearing aid by means of coupling tubing with 2 mm continuous internal diameter, which reflects the most common fitting practice. The tubing is connected to the coupling plate with a nipple of 2 mm internal diameter.

For standardized measurements, an effective coupling tubing length of 43 mm shall be used.

NOTE The 43 mm length consists of 25 mm of standard tubing length plus 18 mm for the earmould and includes the thickness of the coupling plate.



Key

a BTE hearing aid

b Ear hook

c Coupling tubing with 2 mm internal diameter

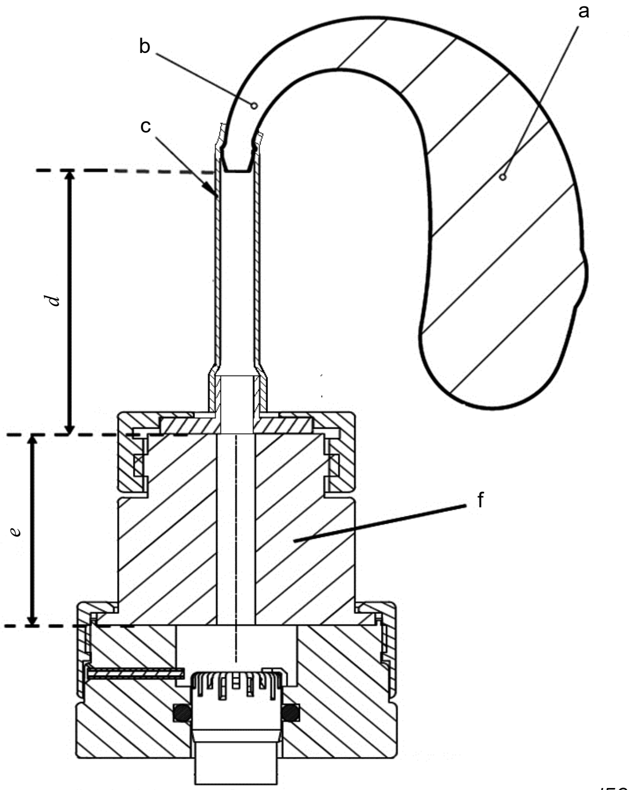
d Coupling plate with a nipple of 2 mm internal diameter

e Effective length of coupling tubing (coupler reference plane to tip of ear-hook)

Figure 5 – Coupling to a BTE hearing aid with 2 mm continuous internal diameter tubing

6.5 Coupling to a BTE hearing aid with earmould simulator

Figure 6 describes coupling to a BTE hearing aid by means of coupling tubing with an effective coupling length of 25 mm and 2 mm internal diameter connected to an earmould simulator with a length of 18 mm and an internal diameter of 3 mm. This configuration is used in IEC 60118-0 and IEC 60118-7 as the standard coupling test setup.



Key

a BTE hearing aid

b Ear hook

c Coupling tubing

d Effective length of coupling tubing

e Length of earmould simulator

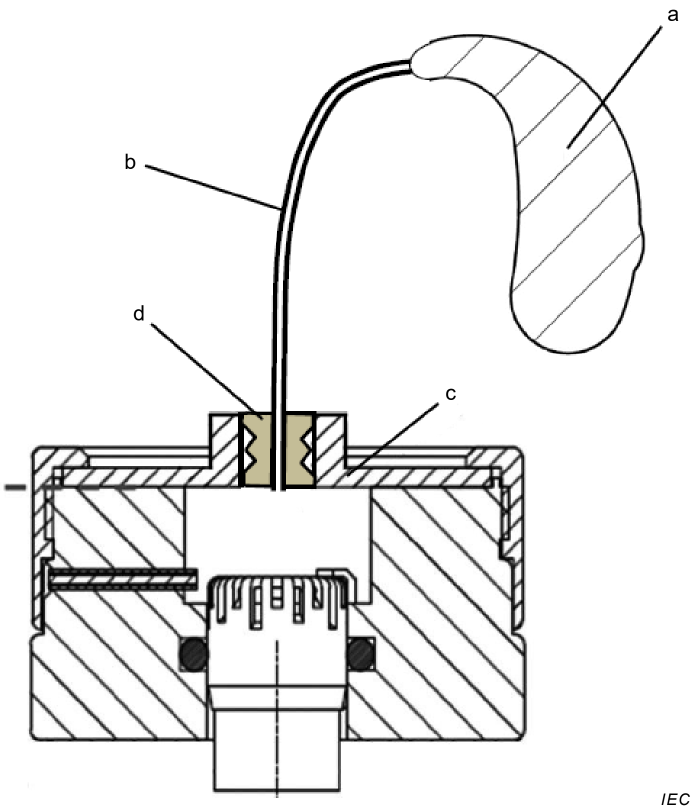
f Earmould simulator

Figure 6 – Coupling to a BTE hearing aid with earmould simulator

6.6 Coupling to a BTE hearing aid with thin tubing

Figure 7 describes coupling of a BTE hearing aid by means of a thin acoustic coupling tubing. Typically, thin coupling tubing is ready made in various shapes and lengths, and have a coupling adapter for attachment of ear-domes. This adapter can be used to insert the tubing into a corresponding bore in the coupling plate. The adapter aligns flush with the coupler reference plane.

If the thin tubing is firmly attached to a custom made earmould, then coupling according to Figure 3 shall be used.



Key

a BTE hearing aid

b Thin coupling tubing

c Coupling plate prepared to accept thin tubing coupling adaptor

d Thin tubing coupling adaptor

Figure 7 – Coupling to a BTE hearing aid with thin coupling tubing

7 Transfer impedance of the 0,4 cm³ coupler

Figure 8 shows the magnitude frequency response of the transfer impedance × frequency and the related equivalent volume. The measurement procedure is described in Annex B.

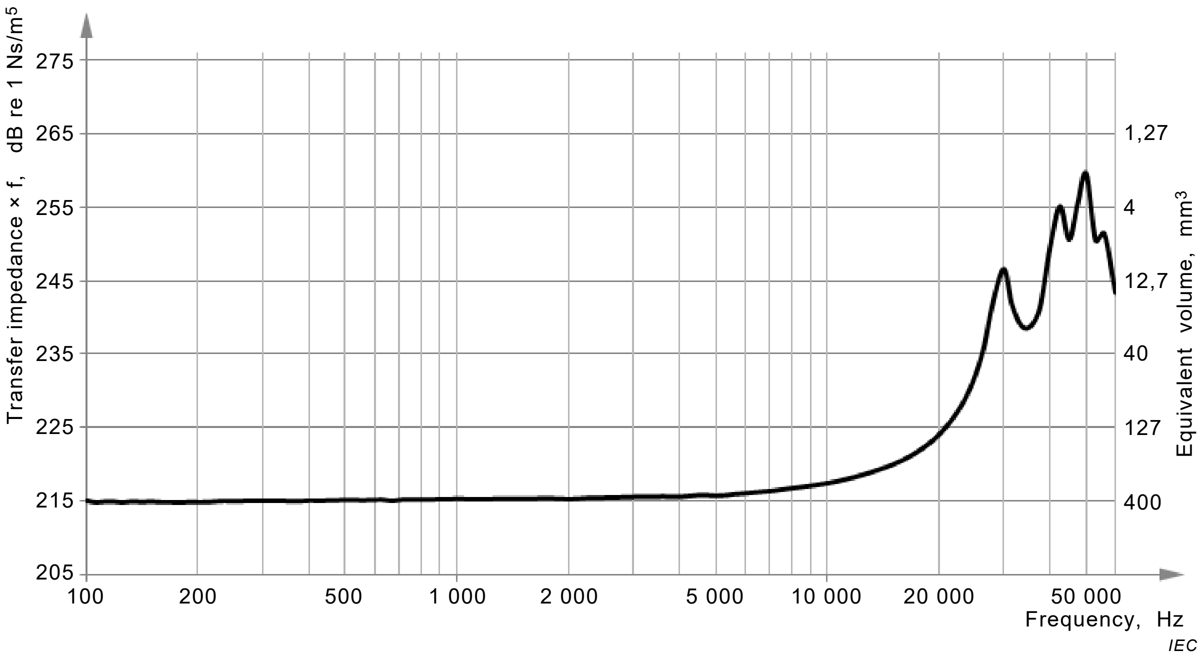


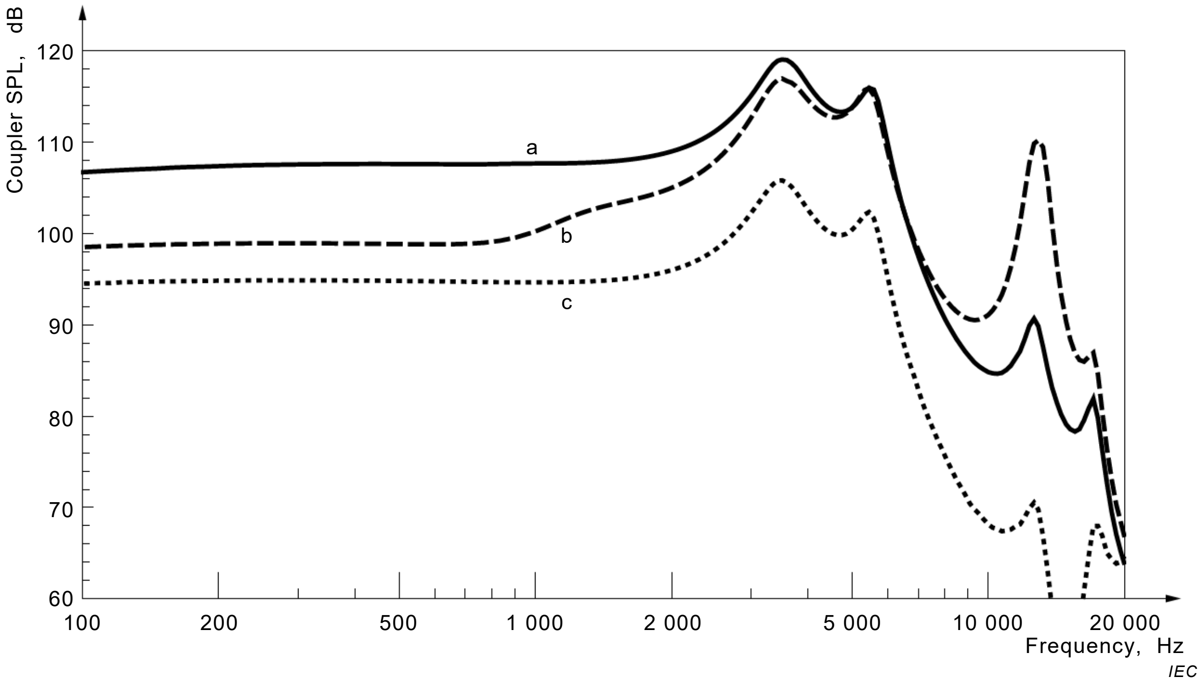
Figure 8 – Magnitude frequency response of the transfer impedance × frequency and the related equivalent volume

8 Comparison of the 0,4 cm³, the 2 cm³ coupler and the occluded-ear simulator

8.1 Sound pressure level frequency response curves

Figure 9 shows examples of SPL responses of a receiver coupled in accordance with Figure 2 to the 0,4 cm³ coupler, the 2 cm³ coupler according to IEC 60318-5 and the occluded-ear simulator according to IEC 60318-4. The 2 cm³ coupler response shows the typical anti-resonance in the 15 kHz to 16 kHz range [1][1]. The occluded-ear simulator response exhibits the typical $\lambda/2$ resonance in the 13,5 kHz range.

[1] Numbers in square brackets refer to the Bibliography.



Key

a Frequency response measured with the 0,4 cm³ coupler

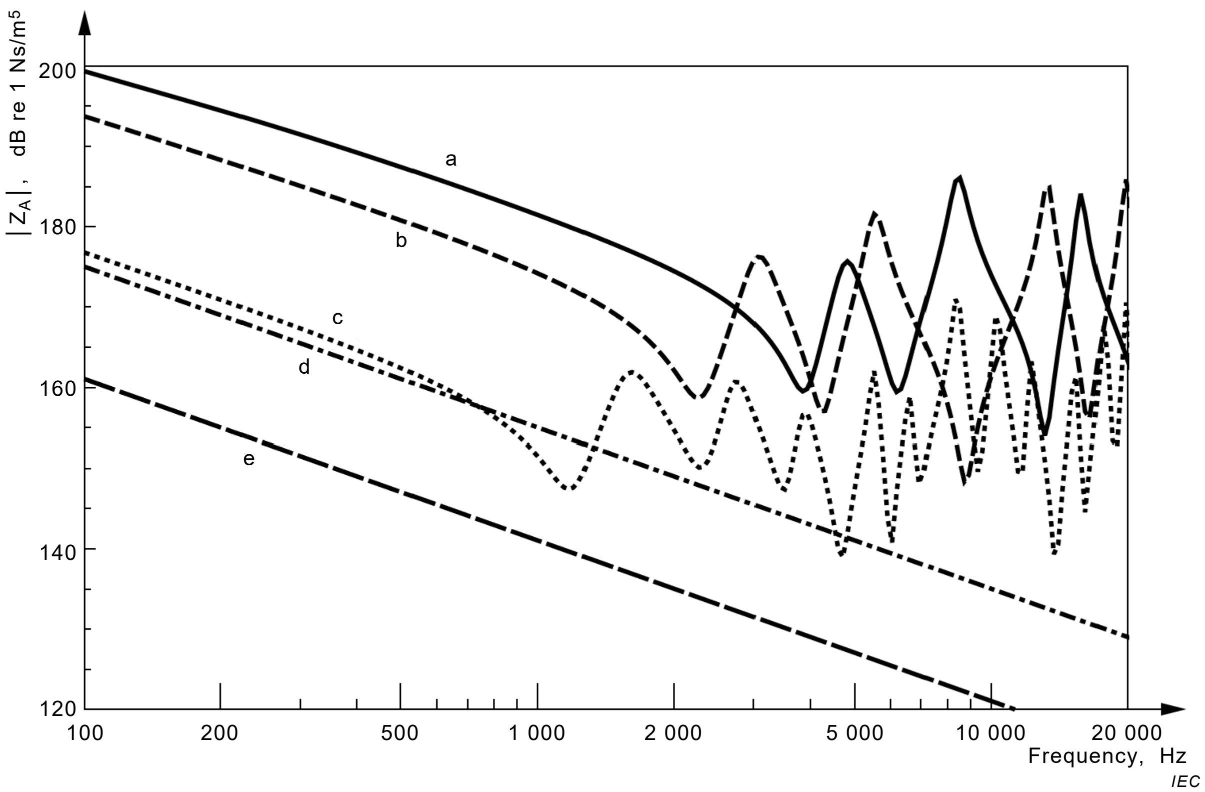
b Frequency response measured with the occluded-ear simulator

c Frequency response measured with the 2 cm³ coupler

Figure 9 – Comparative measurement of the 0,4 cm^3 coupler, the 2 cm^3 coupler and the occluded-ear simulator frequency responses

8.2 Comparison of the coupler impedance with typical source impedances

Figure 10 shows simulated frequency responses of the magnitude of the acoustic input impedance $|Z_A|$ of the 0,4 cm^3, the 2 cm^3 coupler and some typical output impedances of various types of hearing aids. All impedances are measured at the coupler reference plane (Figure 1). Due to the long tubing, the output impedance of a BTE hearing aid is fairly low and, at low frequencies, is similar in magnitude to the impedance of the 0,4 cm^3 coupler.



Key

a CIC hearing aid

b ITE hearing aid

c BTE hearing aid

d 0,4 cm^3 coupler

e 2 cm^3 coupler

Figure 10 – Magnitude frequency responses of acoustic impedance of the 2 cm^3, the 0,4 cm^3 coupler and various hearing aid types

8.3 Influence of sound source impedance on measured level difference between the 0,4 cm^3 coupler and the 2 cm^3 coupler

Percentagewise, the impedance of the sound source has greater influence on the 0,4 cm^3 coupler in comparison to the 2 cm^3 coupler. For this reason, the measured coupler level difference between the output measured with the 0,4 cm^3 coupler and the 2 cm^3 coupler is affected accordingly (see definition in 3.1.4). Figure 11 shows the deviation from the coupler volume ratio (see definition in 3.1.3). The following formula is used:

$$Deviation = 20\log\left(\frac{V_{2\,cm^3} + V_s}{V_{0{,}4\,cm^3} + V_s}\right) dB - 20\log\left(\frac{V_{2\,cm^3}}{V_{0{,}4\,cm^3}}\right) dB$$

where

V_s is the effective volume of the sound source which is the combined volumes of the sound source and control microphone.

The measured coupler level difference between output measured in the 0,4 cm^3 coupler and the 2 cm^3 coupler is within 0,1 dB of the coupler volume ratio (an error of less than 1 %) when the sound source impedance is at least 40 dB higher than the coupler impedance, or the effective volume of the sound source is less than 4 mm^3.

NOTE One method to achieve a high source impedance is to use a setup as per Figure 2, but with an effective length of the coupling tubing of 8 mm and an internal diameter of 0,15 mm.

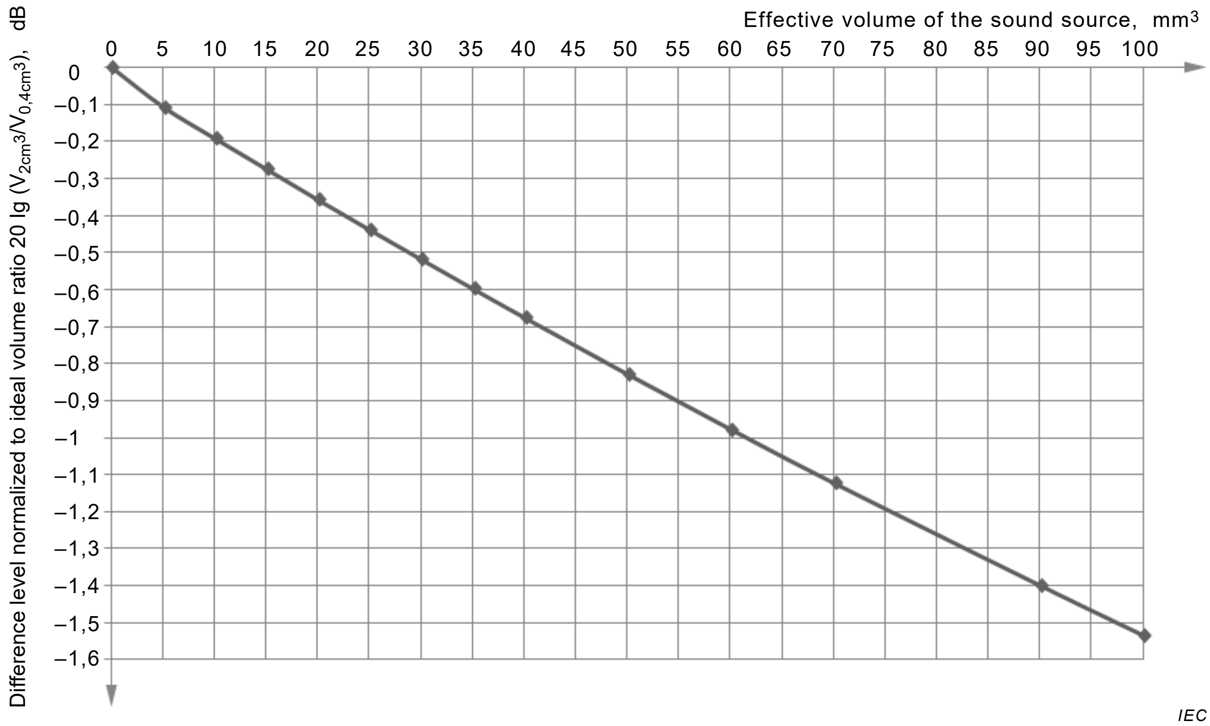


Figure 11 – Deviation from the normalized coupler volume ratio as a function of the effective volume of the sound source V_s

9 Maximum permitted expanded uncertainty for coupler conformance testing

In order to demonstrate conformance with the requirements of this document, the actual expanded uncertainty of measurements (for a probability of 95 %, equivalent to a coverage factor of $k = 2$) performed by the test laboratory shall not exceed the maximum permitted values of U_{max} in Table 1.

See also ISO/IEC Guide 98-3.

Table 1 – Values of U_{max} for basic measurements

Measured quantity	Relevant subclause number	Basic U_{max} (k = 2)
Effective coupler volume	4.2.2	10 mm^3
Height of cylindrical cavity	4.2.2	0,05 mm
Diameter of cylindrical cavity	4.2.3	0,05 mm
Diaphragm position	4.4.1	0,1 mm
Volume of static pressure equalisation vent	4.5	0,5 mm^3
Volume of microphone insertion stop feature	4.3.1	0,2 mm^3
Sound attenuation	4.5	0,1 dB
Ambient pressure	5.2	0,1 kPa
Temperature	5.1	0,5 °C
Relative humidity	5.1	5 %
Internal diameter of coupling tubing or ear-mould substitute	6.4, 6.5	0,02 mm
Length of coupling tubing or earmould substitute	6.4, 6.5	0,02 mm

10 Measurements using the 0,4 cm^3 coupler

10.1 General

The requirements and procedures of IEC 60118-0 shall be followed, with the exception of the measurement frequency range. For measurements according to this document, the 8 kHz frequency limit in IEC 60118-0 is replaced by 16 kHz.

Because of the expanded frequency range, the demand on the requirements for the test enclosure, as well as for the measurement equipment and the care of performing the measurements are increased.

10.2 to 10.5 describe additions to IEC 60118-0 when performing measurements using the 0,4 cm^3 coupler.

10.2 Test enclosure and test equipment

All test enclosure and test equipment requirements of IEC 60118-0 apply with the following additions:

a) the uncertainties in the levels of the sound source shall be within ± 2,5 dB over the range of 8 000 Hz to 16 000 Hz;

b) the equipment for the measurement of the sound pressure level produced by the hearing aid shall meet the requirement that the indication of the sound pressure level relative to the indication at the frequency of calibration shall be measured with an expanded uncertainty of no more than ± 1,5 dB in the frequency range from 8 000 Hz to 16 000 Hz.

10.3 Extended frequency range for total harmonic distortion measurements

Table 2 shows the extended range of distortion test frequencies.

Table 2 – Distortion test frequencies and input sound pressure levels

Distortion test frequency	Input SPL
500 Hz	70 dB
800 Hz	70 dB
1 600 Hz	65 dB
3 150 Hz	60 dB
6 300 Hz	60 dB

10.4 Presentation of data

10.4.1 General

All published curves showing variation of a parameter with frequency shall be plotted according to IEC 60263.

10.4.2 Presentation as 0,4 cm^3 coupler data

All published data obtained with the 0,4 cm^3 coupler shall be clearly labelled "Measured with 0,4 cm^3 coupler according to IEC/TS 62886".

10.4.3 Presentation as normalised to 2 cm^3 coupler data

It is possible to present the data normalised to the values obtained in a 2 cm^3 coupler at 1 kHz. The data shall be labelled with "Measured with 0,4 cm^3 coupler according to IEC/TS 62886 normalized to 2,0 cm^3 coupler data".

10.5 Maximum permitted expanded uncertainty of measurements performed using the 0,4 cm^3 coupler

Table 3 specifies the maximum permitted expanded uncertainty U_{max}, for a probability of 95 % equivalent to coverage factor of k = 2, associated with basic measurements using the coupler described in this document. See also ISO/IEC Guide 98-3.

Table 3 – Values of U_{max} for basic measurements

Measured quantity	U_{max}
Sound pressure level of acoustic input:	
200 Hz to 8 000 Hz	1,5 dB
> 8 000 Hz to 16 000 Hz	2,5 dB
Coupler sound pressure level:	
200 Hz to 8 000 Hz	1 dB
> 8 000 Hz to 16 000 Hz	1,5 dB
Magnetic field strength level:	
200 Hz to 8 000 Hz	1,5 dB
> 8 000 Hz to 16 000 Hz	1,5 dB
Frequency	0,5 %
Total harmonic distortion	0,5 %
Intermodulation distortion	0,5 %
Ambient pressure	0,1 kPa
Temperature	0,5 °C
Relative humidity	5 %

The measurement uncertainty is composed of several factors:

– uncertainty of equipment used, such as sound generators, level meters, measuring microphones, coupler, etc.;
– uncertainties of the acoustic coupling of the hearing aid to the coupler. Such uncertainties could be related to diameter and length of coupling tubing;
– accuracy and care while positioning the hearing aid in the test space.

Annex A
(informative)

Response transforms between the 0,4 cm³ coupler and the occluded-ear simulator

A.1 General

The response transforms described in Annex A allow the prediction of the sound pressure level as it would be measured in an occluded-ear simulator. By means of simulation, the effects of further reduction of the occluded volume, as is the case when using CIC or deep insertion devices, on output data can be derived, which could not be measured directly with an occluded-ear simulator according to IEC 60318-4.

As of the time of publication, there was no reliable data base or test equipment available to describe or measure the real-ear response in the frequency range between 8 kHz and 16 kHz. For this reason, and as a first step, this annex uses the occluded-ear simulator according to IEC 60318-4 as reference rather than the real-ear data. When appropriate real-ear measurement equipment becomes available, the transform curves can be updated to provide average Real-Ear-to-0,4 cm^3 coupler difference curves. Or alternatively, an individual, Real-Ear-to-0,4 cm^3 Coupler Differences (RE04CD) may be measured.

In this annex, transform curves are provided for:

a) Standard-fitting:
12,7 mm occluded canal length, representing fitting at the occluded-ear simulator reference plane. The occluded volume is 0,52 cm^3. The λ/2 resonance is at 13,5 kHz.

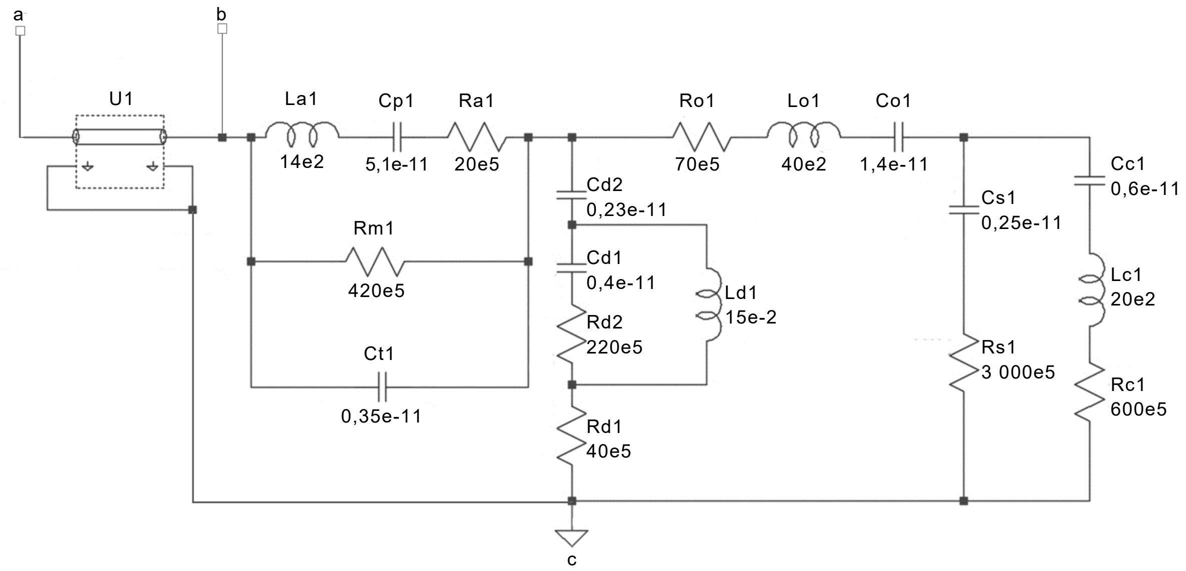
b) CIC-fitting:
9,1 mm occluded canal length, representing insertion depth of a typical CIC hearing aid. The occluded volume is 0,4 cm^3. The λ/2 resonance is at 19 kHz.

c) Deep-insertion-fitting:
6 mm occluded canal length, representing insertion depth of a deep insertion device. The occluded volume is 0,265 cm^3. The λ/2 resonance is at 28 kHz.

A.2 Simulation model of the human ear and approximation of λ/2 resonances

Figure A.1 shows the acoustic analogue circuit of the occluded ear, including tympanic membrane, middle ear and cochlea. The occluded volume, the volume between earmould and tympanic membrane, is explicitly available – simulated by the tube model U1 – and can be adjusted to study the effects of various insertion depths. The model is taken from [11], figure 10; the tube model is described in [2]. The transform curves are composed using the following operations:

– As a basis for modelling, the response curve for standard-fitting is used for frequencies between 125 Hz and 16 kHz. This response curve is obtained by measurement with an occluded-ear simulator and with a 0,4 cm^3 coupler. The measured response is shown in Figure A.3.
– For modelling the responses for CIC- and deep-insertion-fitting below 6 kHz, the response for the standard-fitting is used and adjusted with corresponding corrections. The corrections below 6 kHz are calculated based on results of simulations of frequency response using the ear model (Figure A.1) with occluded canal lengths of 9,1 mm and 6 mm.
– For modelling the responses for CIC- and deep-insertion-fitting above 6 kHz, a band pass filter for approximating the λ/2 resonance is used (see Formula (A.1). The band-pass resonances have a Q-factor of 8 and are centred at 13,5 kHz for standard-fitting, 19 kHz for CIC-fitting and 28 kHz for deep-insertion-fitting.



IEC

Key

a	Entrance to occluded ear canal (input)
b	Tympanic membrane (output)
c	Ground terminal
U1	Tube model with parameters:
	diameter 7,5 mm
	length 12,7 mm, 9,1 mm and 6 mm
L	inductors in H
C	capacitors in F
R	resistors in Ω
e(number)	means 10^{number}
Suffixes to L, C, R:	
a, p, m and t	relate to the middle ear cavities
d	relate to ear drum
o	relate to malleal complex
s	relate to incudo-stapedial joint
c	relate to cochlear

Figure A.1 – Electrical analogue model of the human ear

Formula to approximate the $\lambda/2$ resonance:

$$20 \lg \overrightarrow{\left[\left|\frac{p \times k}{(p \times k)^2 + \frac{p \times k}{Q+1} + 1} + 1\right|\right]} \quad \text{(absolute value of complex data)} \qquad \text{(A.1)}$$

where

Q is the factor of the resonance curve (8);

p = $i \times (2 \times \pi \times f)$, where $i = \sqrt{-1}$ and $f = (\text{data})^{\langle 0 \rangle}$;

$k = \frac{(\pi)}{19{,}75 \times f_{peak}}$, where f_{peak} = (13 800), where f is the frequency scale and f_{peak} is the frequency of resonance peak.

A.3 Measured and simulated transform responses of a standard-fitting

Figure A.2 shows the measured transform response of a hearing aid receiver when coupled to the reference plane of the occluded-ear simulator according to IEC 60318-4. The diameter of the ear canal is 7,5 mm and the distance between earmould and microphone diaphragm is 12,5 mm, thus the occluded ear canal volume is 0,52 cm^3. The $\lambda/2$ resonance is nominally at 13,5 kHz ± 1,5 kHz.

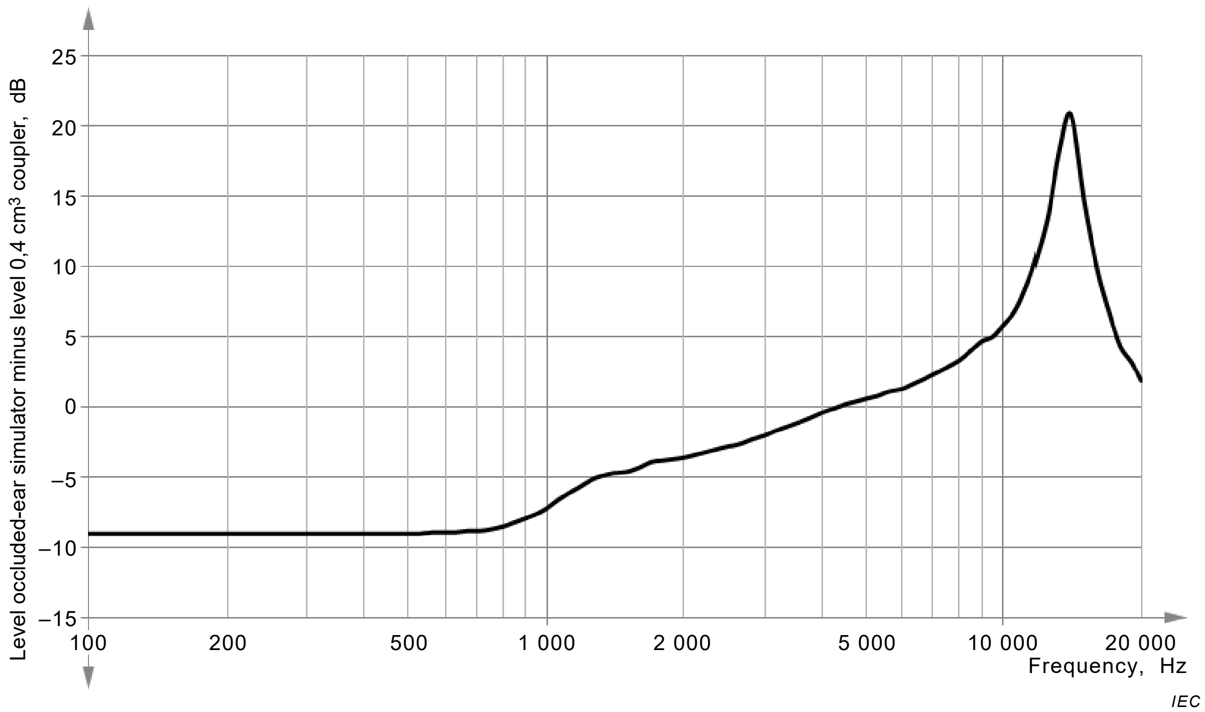


Figure A.2 – Measured transform response of a standard-fitting

Figure A.3 shows the comparison between the measured (solid line) and the simulated transform response. The simulated transform response is composed of two segments as described in A.2.

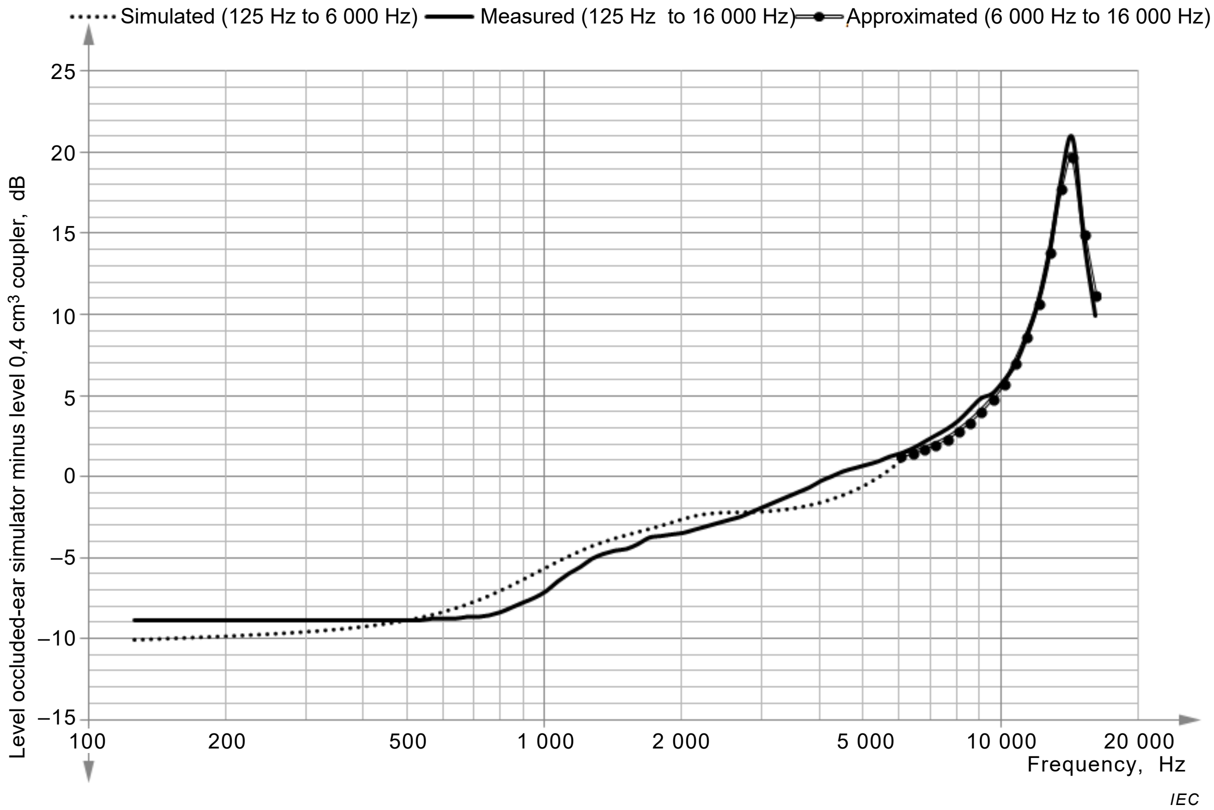


Figure A.3 – Comparison between the measured and the simulated standard-fitting transform response

A.4 Transform curves for CIC-fitting and deep-insertion-fitting

By means of simulation, the occluded canal lengths of 12,5 mm as used in A.2 for standard-fitting is reduced from 12,5 mm to 9,1 mm to simulate the conditions for CIC hearing aids (occluded volume 0,4 cm^3), and to 6 mm to simulate the conditions for a deep inserted hearing device (occluded volume 0,265 cm^3). See Figure A.4.

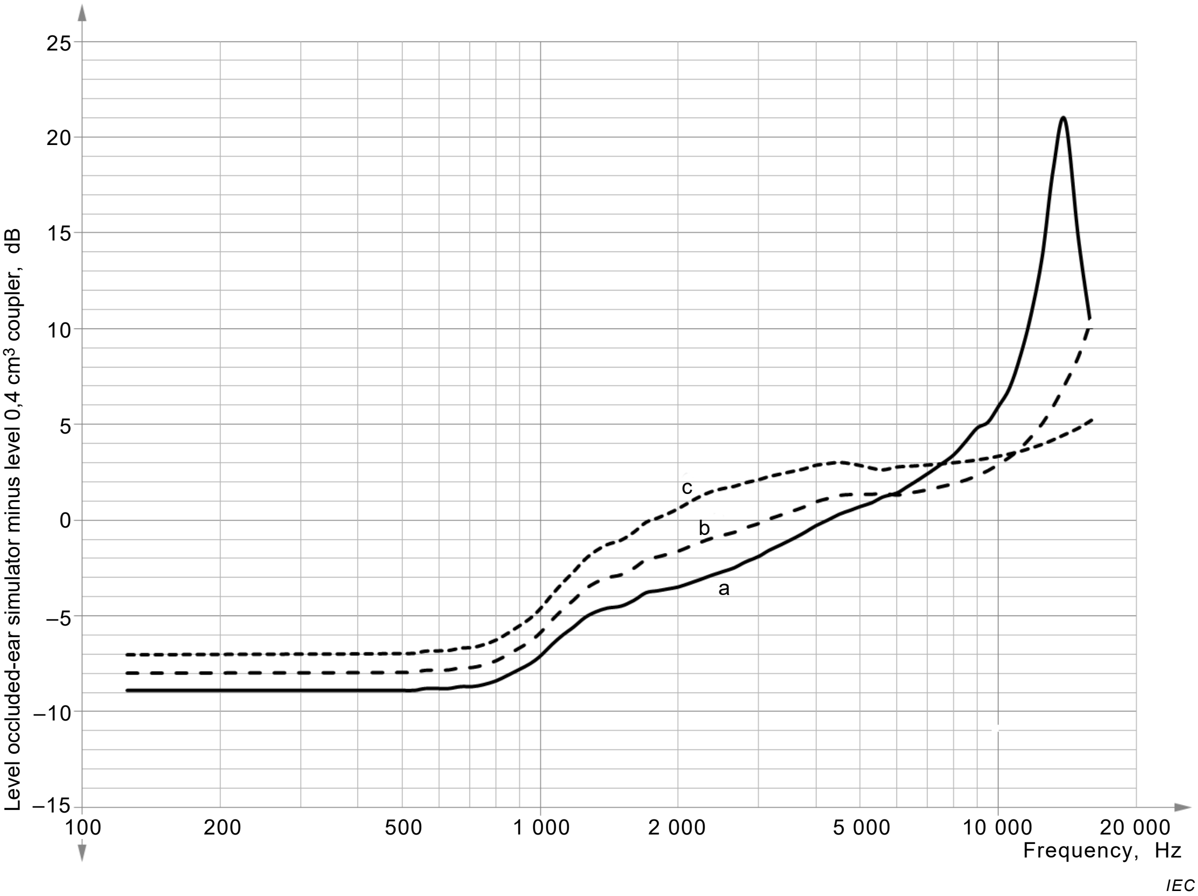


Figure A.4 – Transform responses for (a) standard-fitting, b) CIC-fitting and (c) deep-insertion-fitting

Table A.1 shows the transform data at the ISO R40 preferred frequencies (one-twelfth octaves) [16] in the frequency range from 125 Hz to 16 kHz.

Levels from measurements using the 0,4 cm^3 coupler plus the values in Table A.1 will give an approximation of SPL at the ear drum for the device type listed in each column.

Table A.1 – Transform data for standard-fitting (fitting at reference plane), CIC-fitting and deep-insertion-fitting

	Transform data in dB		
Frequency Hz	**Standard-fitting**	**CIC-fitting**	**Deep-insertion-fitting**
Occluded volume	**550 mm^3**	**400 mm^3**	**200 mm^3**
Length × diameter	**12,5 × 7,5 mm**	**9,1 × 7,5 mm**	**6 × 7,5 mm**
125	-8,90	-7,98	-7,04
132	-8,90	-7,97	-7,03
140	-8,90	-7,97	-7,03
150	-8,90	-7,97	-7,03
160	-8,90	-7,97	-7,03
170	-8,90	-7,97	-7,02
180	-8,90	-7,97	-7,02
190	-8,90	-7,97	-7,02
200	-8,90	-7,96	-7,02
212	-8,90	-7,96	-7,01
224	-8,90	-7,96	-7,01
236	-8,90	-7,96	-7,01
250	-8,90	-7,96	-7,01
265	-8,90	-7,96	-7,00
280	-8,90	-7,96	-7,00
300	-8,90	-7,96	-7,00
315	-8,90	-7,95	-7,00
335	-8,90	-7,95	-7,00
355	-8,90	-7,95	-6,99
375	-8,90	-7,95	-6,99
400	-8,90	-7,95	-6,99
425	-8,90	-7,95	-6,98
450	-8,90	-7,94	-6,98
475	-8,90	-7,94	-6,97
500	-8,90	-7,94	-6,97
530	-8,90	-7,93	-6,96
560	-8,80	-7,82	-6,85
600	-8,80	-7,82	-6,83
630	-8,80	-7,80	-6,81
670	-8,70	-7,69	-6,69
710	-8,70	-7,67	-6,65
750	-8,60	-7,55	-6,51
800	-8,40	-7,33	-6,26
850	-8,10	-6,99	-5,90
900	-7,80	-6,66	-5,52
950	-7,50	-6,31	-5,13
1 000	-7,10	-5,86	-4,62
1 060	-6,50	-5,20	-3,90
1 120	-6,00	-4,64	-3,26
1 180	-5,60	-4,17	-2,71
1 250	-5,10	-3,61	-2,06
1 320	-4,80	-3,25	-1,62
1 400	-4,60	-2,99	-1,28
1 500	-4,50	-2,84	-1,05

	Transform data in dB		
Frequency Hz	**Standard-fitting**	**CIC-fitting**	**Deep-insertion-fitting**
1 600	-4,20	-2,50	-0,64
1 700	-3,80	-2,06	-0,12
1 800	-3,70	-1,92	0,10
1 900	-3,60	-1,77	0,33
2 000	-3,50	-1,61	0,59
2 120	-3,30	-1,37	0,94
2 240	-3,10	-1,14	1,24
2 360	-2,90	-0,95	1,48
2 500	-2,70	-0,78	1,64
2 650	-2,50	-0,63	1,75
2 800	-2,20	-0,40	1,94
3 000	-1,90	-0,17	2,10
3 150	-1,60	0,05	2,26
3 350	-1,30	0,27	2,40
3 550	-1,00	0,48	2,54
3 750	-0,70	0,67	2,65
4 000	-0,30	0,96	2,86
4 250	0,00	1,14	2,94
4 500	0,30	1,30	3,01
4 750	0,50	1,34	2,94
5 000	0,70	1,36	2,84
5 300	0,90	1,35	2,70
5 600	1,20	1,41	2,62
6 000	1,40	1,31	2,76
6 300	1,70	1,40	2,80
6 700	2,10	1,50	2,84
7 100	2,50	1,61	2,88
7 500	2,90	1,75	2,93
8 000	3,40	1,91	2,99
8 500	4,10	2,10	3,06
9 000	4,80	2,32	3,13
9 500	5,10	2,58	3,22
10 000	5,90	2,90	3,33
10 600	6,90	3,29	3,45
11 200	8,60	3,76	3,59
11 800	10,70	4,33	3,76
12 500	13,80	5,05	3,95
13 200	18,30	5,94	4,19
14 000	20,90	7,08	4,46
15 000	14,60	8,56	4,80
16 000	9,90	10,50	5,20

Annex B
(informative)

Measurement and modelling of the transfer impedance of the 0,4 cm³ coupler

B.1 Measurement procedure

B.1.1 Transfer impedance

The acoustic transfer impedance of the 0,4 cm^3 coupler is similar to the transfer impedance of a pure volume at low frequencies, while at high frequencies the first half-wave resonance at approximately 30 kHz will influence the impedance.

To measure the transfer impedance of the coupler, a sound source with a known frequency independent volume velocity (f) is used. The transfer impedance Z_A is proportional to the measured output sound pressure:

$$|Z_A|(f) = \frac{p(f)}{q(f)} \quad \text{(B.1)}$$

B.1.2 Calibration of the volume velocity source at 250 Hz

At 250 Hz, the coupler behaves as a pure volume with well-defined compliance. The coupler impedance Z_{A250} can be determined by calculation based on the volume of a calibrated 0,4 cm^3 coupler.

$$Z_{A250} = \frac{1}{j\omega C_a} \quad \text{(B.2)}$$

$$C_a = \frac{v}{\rho c^2} \quad \text{(B.3)}$$

where

C_a is the acoustic compliance of a volume (20 °C, 101,325 kPa)

ρ is the density of air (1,2041 kg/m³)

c is the speed of sound in air (343,21 m/s)

The transfer impedance of the coupler Z_A at 250 Hz is calculated from Formulas (B.2) and (B.3) as

– 225,7 x 10^6 Ns/m^5, or
– 167 dB re 1 Ns/m^5, or
– 215 Ns/m^5 x f.

The output level of the volume velocity source should be chosen so that noise and saturation issues are avoided. Typically, this is achieved by a coupler SPL of 74 dB (0,1 Pa) at 250 Hz.

$$q_{250} = \frac{p_{250}}{Z_{A250}} \quad \text{(B.4)}$$

With the above data, the volume velocity q at 250 Hz is 44,3 x 10^{-9} m^3/s.

B.1.3 Calibration of the volume velocity source over the frequency range from 100 Hz to 60 kHz

The procedure is based on the method of calibration of the microphone frequency response as described in IEC 61094-6:

a) the microphone is calibrated at 250 Hz by means of a pistonphone;

b) an electrostatic actuator is attached to the microphone. The electrostatic field of the actuator will excite the microphone diaphragm to the same excursion for all frequencies of interest.

For reasons of convenience, the calibration data obtained with the actuator (H_{Actuator}) is normalized to the calibration value at 250 Hz (measured with a pistonphone) and referred to as the relative transmitter transfer function $H_{\text{Tr,Rel}}$.

$$H_{\text{Tr,Rel}} = H_{\text{Actuator}} \frac{f}{f_{250}} \qquad \text{(B.5)}$$

The frequency response of the volume velocity is calculated as:

$$Q(f) = H_{\text{Tr,Rel}}(f) \times q_{250} \qquad \text{(B.6)}$$

B.1.4 Test set-up for measuring the coupler transfer impedance

Figure B.1 illustrates the test set-up.

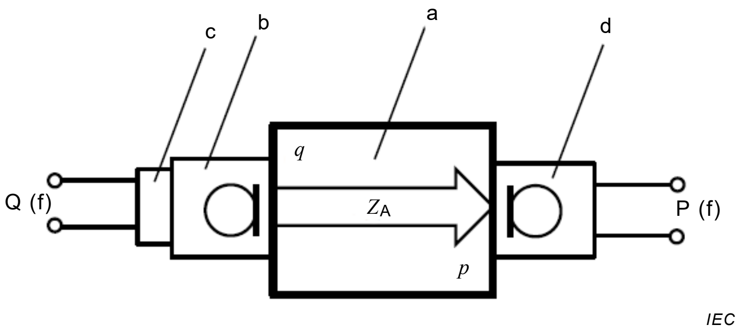
A condenser microphone with a diaphragm of 3 mm diameter is used as the volume velocity source which is attached to the coupler reference plane. Care should be taken to align the microphone diaphragm flush with the coupler reference plane to avoid any offset of the coupler volume.

The input signal is fed into the microphone by means of a microphone transmitter adapter.

The output signal is taken from the WS3P coupler microphone, as specified in this document.

From pressure measurements conducted with the 0,4 cm^3 coupler, the frequency response of the coupler transfer impedance $|Z_A|(f)$ is given by:

$$|Z_A|(f) = \frac{p(f)}{Q(f)} \qquad \text{(B.7)}$$



Key

a 0,4 cm^3 coupler with calibrated volume

b microphone as sound source (transmitter)

c microphone transmitter adapter

d coupler microphone (type WS3P with standard sensitivity)

q volume velocity in m^3/s

p sound pressure in N/m^2

Figure B.1 – Test set-up for measuring the coupler transfer impedance

B.2 Measurement of the coupler transfer impedance

Eight coupler samples with calibrated coupler volumes ranging from 0,394 cm^3 to 0,404 cm^3 are measured in the frequency range from 100 Hz to 60 kHz.

A coupler microphone of type WP3P with standard sensitivity is used. Measurements are valid for this type only.

Figure B.2 shows the frequency response of the average of 8 coupler measurements.

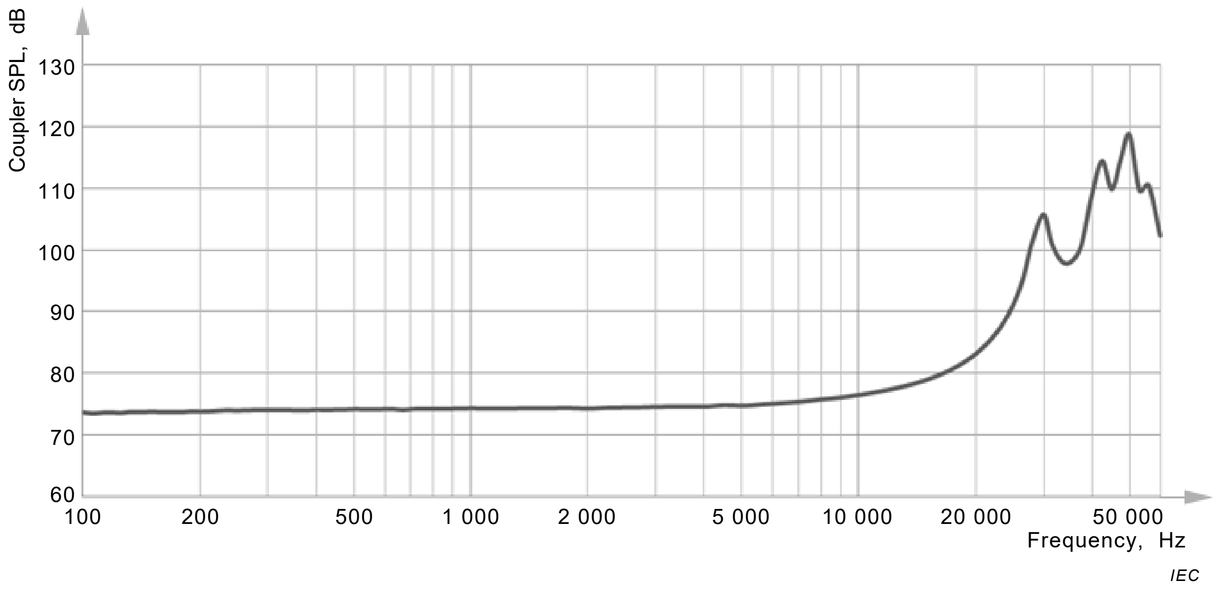


Figure B.2 – Average frequency response of 8 coupler measurements

The average pressure is used to calculate the average transfer impedance shown in Figure B.3.

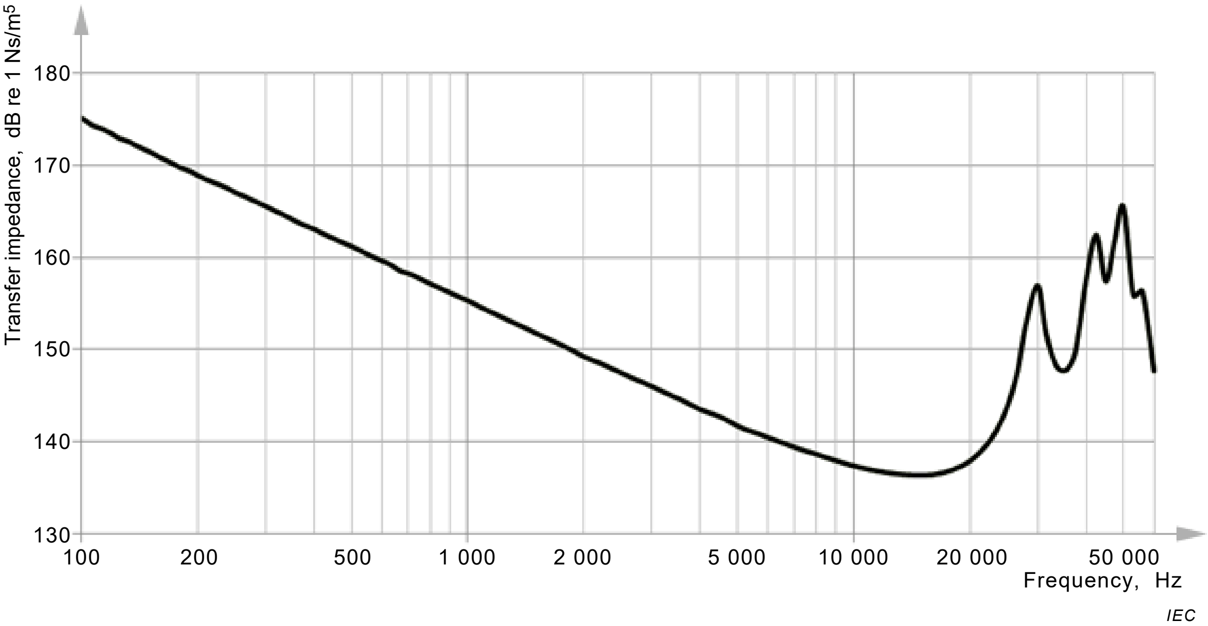


Figure B.3 – Average transfer impedance of the 0,4 cm^3 coupler

In Figure B.4, the transfer impedance is shown as transfer impedance × frequency and as equivalent volume.

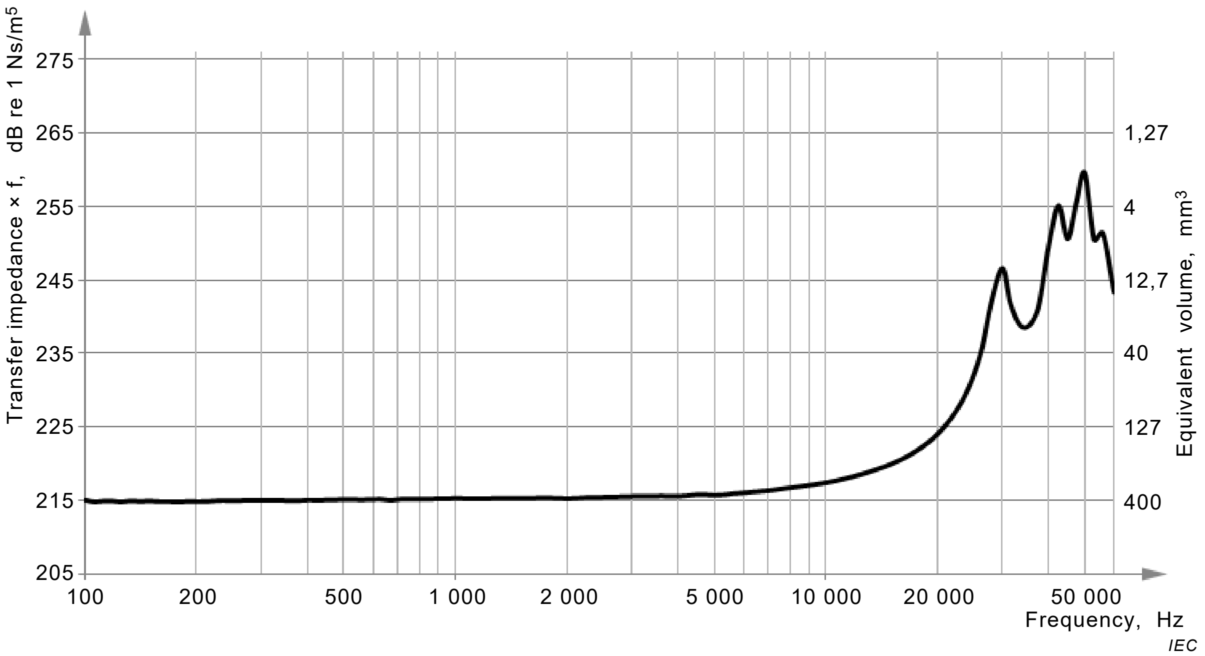


Figure B.4 – Transfer impedance times frequency re 1 Pa/m^3 in dB and as equivalent volume in mm^3 in the frequency range 100 Hz to 60 kHz

Table B.1 contains the data for the transfer impedance $|Z_A|$ re 1 Ns/m^5 in dB, the transfer impedance times frequency $|Z_A| \times f$ re 1 N/m^5 in dB and the equivalent volume in [mm^3] in the frequency range from 100 Hz to 60 kHz (valid for WS3P microphone with standard sensitivity).

Table B.1 – Transfer impedance of the 0,4 cm^3 coupler in the frequency range from 100 Hz to 60 kHz

Frequency	$\lvert Z_A \rvert$ re 1 Ns/m^5	$\lvert Z_A \rvert \times f$ re 1 N/m^5	Equivalent volume		Frequency	$\lvert Z_A \rvert$ re 1 Ns/m^5	$\lvert Z_A \rvert \times f$ re 1 N/m^5	Equivalent volume
Hz	dB	dB	mm^3		Hz	dB	dB	mm^3
100	175,06	215,10	395,44		2 500	147,49	215,49	378,22
106	174,32	214,87	406,28		2 650	146,98	215,48	378,38
112	173,94	214,97	401,60		2 800	146,58	215,56	374,97
118	173,50	214,98	400,89		3 000	146,02	215,60	373,35
125	172,88	214,86	406,75		3 150	145,60	215,61	373,08
132	172,54	214,99	400,49		3 350	145,07	215,61	372,82
140	171,97	214,93	403,16		3 550	144,61	215,66	370,94
150	171,41	214,97	401,44		3 750	144,11	215,63	371,93
160	170,77	214,89	405,11		4 000	143,53	215,61	372,96
170	170,24	214,89	405,30		4 250	143,13	215,73	367,62
180	169,69	214,84	407,58		4 500	142,75	215,85	362,57
190	169,33	214,95	402,49		4 750	142,25	215,82	363,92
200	168,83	214,89	405,18		5 000	141,74	215,76	366,35
212	168,34	214,90	404,49		5 300	141,30	215,83	363,78
224	167,95	214,99	400,31		5 600	140,97	215,97	357,60
236	167,56	215,06	397,32		6 000	140,50	216,10	352,47
250	167,00	215,00	400,00		6 300	140,17	216,19	348,74
265	166,55	215,05	397,64		6 700	139,75	216,31	343,88
280	166,09	215,07	396,84		7 100	139,36	216,43	339,40
300	165,51	215,09	395,88		7 500	139,04	216,58	333,37
315	165,07	215,08	396,58		8 000	138,68	216,78	325,74
335	164,54	215,08	396,53		8 500	138,31	216,94	319,85
355	163,98	215,03	398,81		9 000	137,98	217,10	314,01
375	163,50	215,02	398,97		9 500	137,69	217,28	307,70
400	163,04	215,12	394,72		10 000	137,42	217,46	301,33
425	162,47	215,08	396,36		10 600	137,16	217,71	292,84
450	162,01	215,12	394,78		11 200	136,96	217,98	283,71
475	161,57	215,14	393,51		11 800	136,79	218,26	274,70
500	161,18	215,20	391,00		12 500	136,63	218,61	264,03
530	160,66	215,18	391,64		13 200	136,52	218,97	253,17
560	160,15	215,15	393,09		14 000	136,45	219,42	240,58
600	159,60	215,21	390,59		15 000	136,41	219,97	225,81
630	159,19	215,22	390,01		16 000	136,47	220,59	210,08
670	158,51	215,07	396,78		17 000	136,66	221,31	193,46
710	158,17	215,23	389,38		18 000	136,98	222,12	176,19
750	157,69	215,24	389,33		19 000	137,39	223,01	159,08
800	157,14	215,24	389,19		20 000	137,95	224,01	141,79
850	156,62	215,25	388,61		21 200	138,86	225,43	120,43
900	156,16	215,29	387,07		22 400	140,01	227,06	99,85
950	155,70	215,30	386,67		23 600	141,51	229,01	79,74
1 000	155,31	215,35	384,32		25 000	143,86	231,85	57,46
1 060	154,76	215,31	386,01		26 500	147,45	235,95	35,85
1 120	154,27	215,30	386,64		28 000	152,96	241,95	17,98
1 180	153,83	215,31	385,91		30 000	156,93	246,52	10,62
1 250	153,34	215,32	385,57		31 500	151,76	241,76	18,37
1 320	152,88	215,33	384,99		33 500	148,23	238,77	25,92

Frequency	$\lvert Z_A \rvert$ re 1 Ns/m^5	$\lvert Z_A \rvert \times f$ re 1 N/m^5	Equivalent volume	Frequency	$\lvert Z_A \rvert$ re 1 Ns/m^5	$\lvert Z_A \rvert \times f$ re 1 N/m^5	Equivalent volume
Hz	dB	dB	mm^3	Hz	dB	dB	mm^3
1 400	152,40	215,36	383,83	35 500	147,78	238,82	25,76
1 500	151,79	215,35	384,37	37 500	149,70	241,22	19,54
1 600	151,25	215,37	383,45	40 000	157,46	249,54	7,50
1 700	150,74	215,39	382,39	42 500	162,42	255,03	3,99
1 800	150,25	215,39	382,41	45 000	157,40	250,51	6,71
1 900	149,73	215,35	384,40	47 500	161,90	255,47	3,79
2 000	149,23	215,29	386,77	50 000	165,44	259,46	2,39
2 120	148,80	215,37	383,49	53 000	155,92	250,45	6,76
2 240	148,40	215,45	380,02	56 000	156,29	251,29	6,13
2 360	148,96	215,46	379,34	60 000	147,69	243,30	15,39

B.3 Electrical analogue representation of the coupler as a tube model

To simulate hearing aid or receiver performance below 10 kHz, it is sufficient to model the 0,4 cm^3 coupler as an acoustical compliance of $2{,}82 x 10^{-12} \frac{m^4 s^2}{kg}$ or an electrical capacitance of $2{,}82 x 10^{-12}$ F .

When precision is required up to 25 kHz, such as when coupler data is being used for the high frequency calibration of receiver models, it is desirable to express the measured transfer impedance data from B.2 as a two-port model.

The resonant peak at 30 kHz indicates the use of a lossy transmission line tube model as described by Keefe [12]. However, the observation at the lowest frequencies of a slight downward trend of the equivalent volume (see Table B.1) over frequency indicates a more complex behaviour, as the lossy cylindrical cavity, as described by Biagi & Cook [9] who include thermal losses at the opposing end caps of a closed cylinder, are absent in the lossy transmission line model. It is not feasible to translate the formal solutions of the lossy cavity directly into a form suitable for circuit simulation tools, so the frequency dependant thermal loss and acoustic reactance of the end caps are represented by semi-capacitors. A semi-capacitor is a one-port device with admittance proportional to the square root of the Laplace s, and can be modelled in Spice simulators as a voltage controlled voltage source.

subckt Semicapacitor p n params:k=1	(sub-circuit of a semi-capacitor with terminals p and n)
G1 p n p n laplace={k}*sqrt(s)	(G1 p n p n is the transfer function of a semi-capacitor; {k} value of semi-capacitor in F)
ends	

The resulting model for the coupler is a lossy tube with equal semi-capacitors in shunt across both ports as shown in Figure B.5. The semi-capacitance value is initially unknown but can be estimated by comparing the predicted transfer impedance of the model to the measurement. However, since this model is an imperfect simplification, better agreement is found when the tube in the model is slightly longer and narrower than the coupler itself. Final values of the semi-capacitance and length and diameter of the lossy tube are determined by a non-linear least squares fit of the effective volume implied by the model to the measured effective volume.

Figure B.5 shows the implementation based on a tube model [12] terminated by semi-capacitors.

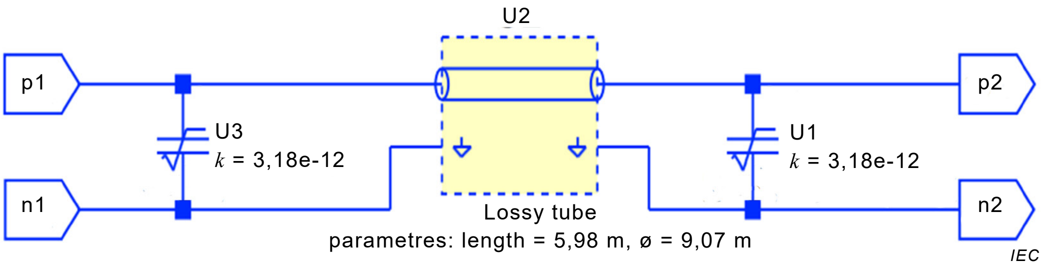


Figure B.5 – Electrical analogue model based on a tube model

Figure B.6 shows the comparison between the measured and the simulated transfer impedance data. The deviation in the frequency range up to 16 kHz is less than 0,2 dB.

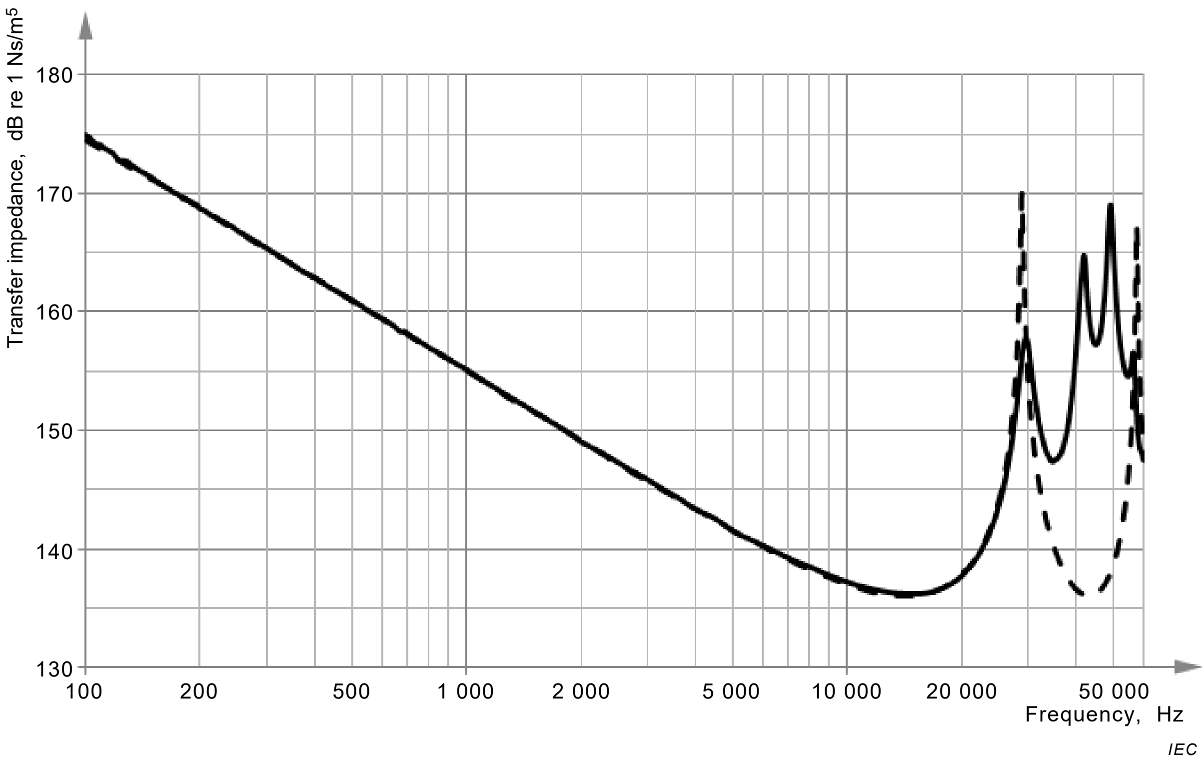
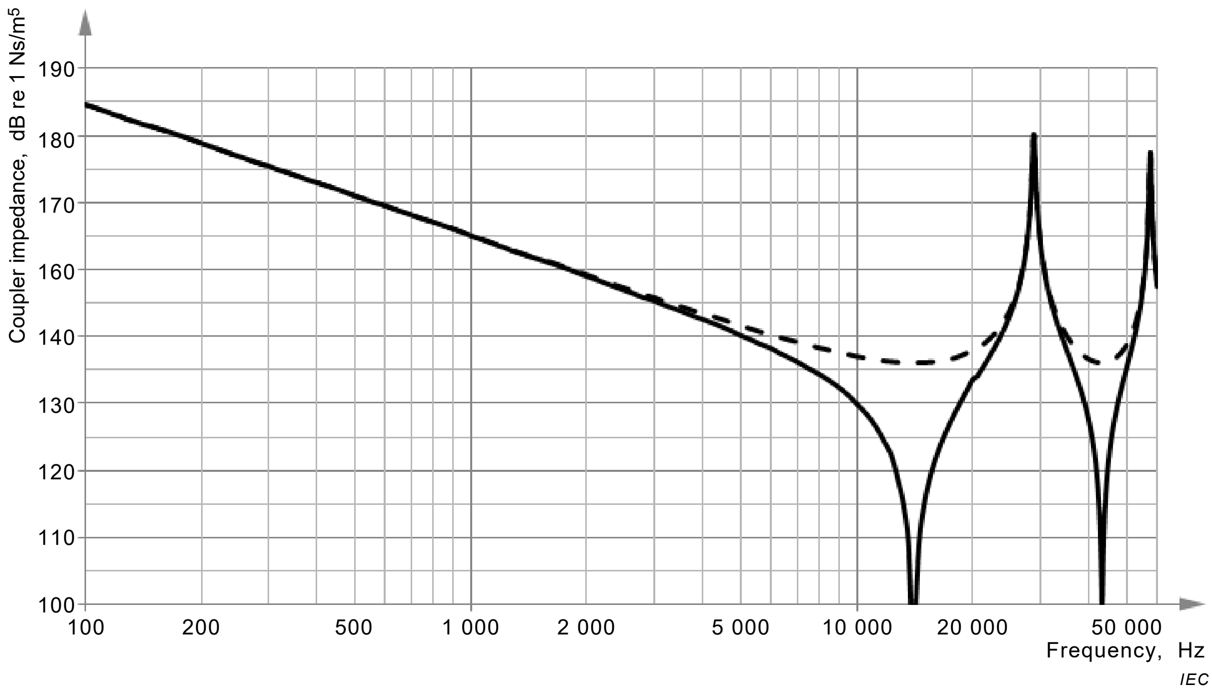


Figure B.6 – Comparison between the measured (solid line) and the simulated (dashed line) transfer impedance

Figure B.7 shows the frequency response of the transfer impedance of the coupler in comparison with the input impedance at the coupler reference plane.



Key

solid line – coupler transfer impedance

dashed line – coupler input impedance

Figure B.7 – Frequency responses of simulated 0,4 cm^3 coupler input and transfer impedances

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