# INTERNATIONAL STANDARD

# ISO 10534-1

First edition
1996-12-15

## Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes —

## Part 1:
Method using standing wave ratio

*Acoustique — Détermination du facteur d'absorption acoustique et de l'impédance acoustique à l'aide du tube d'impédance —*

*Partie 1: Méthode du taux d'ondes stationnaires*



Reference number
ISO 10534-1:1996(E)

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International Organization for Standardization
Case Postale 56 • CH-1211 Genève 20 • Switzerland

Printed in Switzerland

# Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 10534-1 was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 2, *Building acoustics*.

ISO 10534 consists of the following parts, under the general title *Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes*:

— *Part 1: Method using standing wave ratio*

— *Part 2: Method using two microphones*

Annexes A, B and C form an integral part of this part of ISO 10534. Annex D is for information only.

# Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes —

## Part 1:
Method using standing wave ratio

## 1 Scope

**1.1** This part of ISO 10534 specifies a method for the determination of the sound absorption coefficient, reflection factor and surface impedance or surface admittance of materials and objects. The values are determined for normal sound incidence by evaluation of the standing wave pattern of a plane wave in a tube, which is generated by the superposition of an incident sinusoidal plane wave with the plane wave reflected from the test object.

This method can be used for the determination of the sound absorption coefficient of sound absorbers for normal sound incidence. It can further be used for the determination of the acoustical surface impedance or surface admittance of sound-absorbing materials. It is well suited for parameter studies and for the design of sound absorbers, because only small samples of the absorber material are needed.

**1.2** There are some characteristic differences between this method and the measurement of sound absorption in a reverberation room (see ISO 354).

The impedance tube method can be used for the determination of the reflection factor and also the impedance or admittance. The sound is incident normally on the object surface. The reverberation room method will (under idealized conditions) determine the sound absorption coefficient for random sound incidence.

The impedance tube method relies on the existence of a plane incident sound wave and gives exact values under this condition (measuring and mounting errors excluded). The evaluation of the sound absorption coefficient in a reverberation room is based on a number of simplifying and approximate assumptions concerning the sound field and the size of the absorber. Sound absorption coefficients exceeding the value 1 are therefore sometimes obtained.

The impedance tube method requires samples of the test object which are the size of the cross-sectional area of the impedance tube. The reverberation room method requires test objects which are rather large and can also be applied to test objects with pronounced structures in the lateral and/or normal directions. Measurements with such objects in the impedance tube must be interpreted with care (see 9.1).

For the computational transformation of the test results from the impedance tube method (normal incidence) to the situation of diffuse sound incidence, see annex D.

**1.3** This part of ISO 10534 gives preference to numerical methods of evaluation instead of graphical methods, because computers which can perform these computations are assumed to be available. Some of the quantities in the formulae are complex. The arguments of trigonometric functions are in radians.

## 2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of ISO 10534. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of ISO 10534 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 266:—1), *Acoustics — Preferred frequencies.*

ISO 354:1985, *Acoustics — Measurement of sound absorption in a reverberation room.*

## 3 Definitions

For the purposes of this part of ISO 10534, the following definitions apply.

**3.1 sound absorption coefficient, $\alpha$:** Ratio of the sound power entering the surface of the test object (without return) to the incident sound power for a plane wave at normal incidence.

**3.2 sound pressure reflection factor at normal incidence, $r$:** Complex ratio of the pressure amplitude of the reflected wave to the incident wave in the reference plane for a plane wave at normal incidence.

**3.3 reference plane:** Cross-section of the impedance tube for which the reflection factor $r$ or the impedance $Z$ or the admittance $G$ are determined and which is usually the surface of flat test objects. It is assumed to be at $x = 0$.

**3.4 field impedance, $Z(x)$:** Ratio of the sound pressure $p(x)$ to the particle velocity $v(x)$ (directed into the test object) at a point $x$ in the sound field.

**3.5 impedance in the reference plane, $Z_r$:** Ratio at the reference plane of the sound pressure $p$ to the sound particle velocity $v$:

$$Z_r = p/v$$

**3.6 surface impedance, $Z$:** Complex ratio of the sound pressure $p(0)$ to the normal component of the sound particle velocity $v(0)$ at the reference plane.

**3.7 surface admittance, $G$:** Complex ratio of the normal component of the sound particle velocity $v(0)$ to the sound pressure $p(0)$ in the reference plane.

**3.8 surface admittance, $G_s$:** Admittance component at, and normal to, the surface of the test object.

**3.9 characteristic impedance, $Z_0$:** Field impedance (in the direction of propagation) in a single plane wave:

$$Z_0 = \rho_0 c_0$$

where

$\rho_0$ is the density of the medium (air);

$c_0$ is the speed of sound in the medium.

**3.10 normalized impedance, $z$:** Ratio of the impedance $Z$ to the characteristic impedance $Z_0$:

$$z = Z/Z_0$$

**3.11 normalized admittance, $g$:** Product of the admittance $G$ and the characteristic impedance $Z_0$:

$$g = Z_0 G$$

**3.12 standing wave ratio, $s$:** Ratio of the sound pressure amplitude at a pressure maximum, $|p_{max}|$, to that at an adjacent pressure minimum, $|p_{min}|$ (if necessary after correction for varying values at the minima due to sound attenuation in the impedance tube):

$$s = |p_{max}|/|p_{min}|$$

**3.13 standing wave ratio with attenuation, $s_n$:** Standing wave ratio of the $n^{th}$ maximum to the $n^{th}$ minimum.

**3.14 free-field wave number, $k_0$:**

$$k_0 = \omega/c_0 = 2\pi f/c_0$$

where

$\omega$ is the angular frequency;

$f$ is the frequency;

$c_0$ is the speed of sound.

In general the wave number is complex, so

$$k_0 = k_0' - jk_0''$$

where

$k_0'$ is the real component ($k_0' = 2\pi/\lambda_0$);

$k_0''$ is the imaginary component which is the attenuation constant in nepers per metre.

**3.15 phase of reflection (factor), $\Phi$:** Results from the representation of the complex reflection factor by magnitude and phase:

$$r = r' + jr'' = |r| \cdot e^{j\Phi} = |r|(\cos\Phi + j\sin\Phi)$$

$$|r| = \sqrt{r'^2 + r''^2}$$

$$\Phi = \arctan\frac{r''}{r'}$$

$$r' = |r|\cos\Phi$$

$$r'' = |r|\sin\Phi$$

1) To be published. (Revision of ISO 266:1975)

**3.16 working frequency range,** $f$: Range within which measurements can be performed in a given impedance tube:

$$f_l < f < f_u$$

where $f_l$ and $f_u$ are the lower and upper frequency limits, respectively.

**3.17 test section:** Section of the impedance tube with no higher modes, in which the standing wave can be explored.

**3.18 installation section:** Section of the impedance tube in which the test object is installed.

## 4 Principle

The test object is mounted at one end of a straight, rigid, smooth impedance tube which is a tight fit (see figure 1). The incident plane sinusoidal sound wave $p_i$ is generated by a loudspeaker at the other end of the tube. The superposition $p = p_i + p_r$ of the incident wave $p_i$ with the wave reflected from the test object, $p_r$, produces a standing wave pattern in the tube. The evaluation proceeds from the measured quantities (either in a linear or in a logarithmic scale) of the sound pressure amplitudes $|p(x_{min})|$ at pressure minima (one or more), and $|p(x_{max})|$ at pressure maxima. These data are sufficient to determine the sound absorption coefficient. In addition, the distance $x_{min,1}$ of the first sound pressure minimum from the reference plane at $x = 0$ (which is usually the plane where the surface of the test object is placed), and the sound wavelength $\lambda_0$ must be determined to give the reflection factor $r$ and the impedance $Z$ or the admittance $G = 1/Z$.

## 5 Fundamentals

### 5.1 General conditions

The method of this part of ISO 10534 relies heavily on the fact that there exist only plane incident and reflected waves propagating parallel to the tube axis in the test section of the tube (the section where the standing wave pattern is explored). The generation of other wave forms (higher modes) shall be avoided (see annex B). It is further assumed that the sound wave propagates in the tube without attenuation. Corrections can be applied for residual attenuations due to friction and thermal losses at the tube walls. Methods for the determination of these corrections are given in annex A.

### 5.2 Formulae

NOTE 1 The time factor $e^{j\omega t}$ is omitted in the following formulae.

The incident sound wave $p_i$ is assumed to be plane, harmonic in time with frequency $f$ and angular frequency $\omega = 2\pi f$, without attenuation (for a correction of attenuation, see annex A), and directed along the axis of the impedance tube (in the negative $x$-direction)

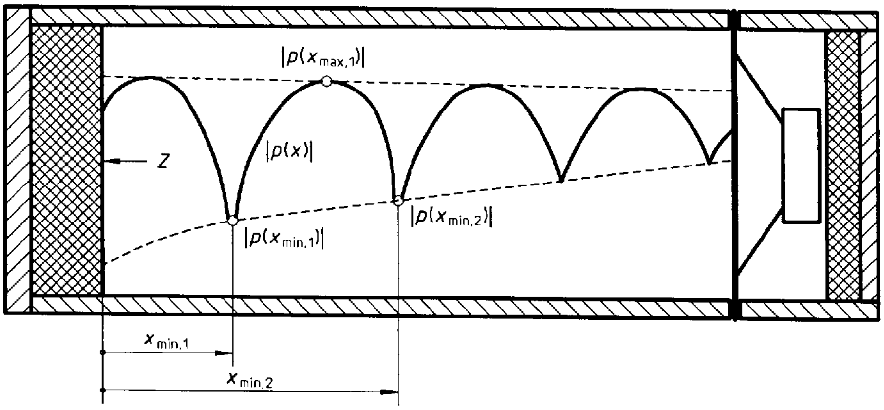
$$p_i(x) = p_0 e^{jk_0 x} \quad \ldots (1)$$

$$k_0 = \frac{\omega}{c_0} = \frac{2\pi f}{c_0} \quad \ldots (2)$$

where the amplitude $p_0$ is arbitrary.

The wave which is reflected from the test object having a reflection factor $r$ is then

$$p_r(x) = r \cdot p_0 \cdot e^{-jk_0 x} \quad \ldots (3)$$




NOTE — The first pressure maximum to be measured shall normally be chosen to lie between the first two minima, as shown.

**Figure 1 — Standing wave pattern in a test tube**

The particle velocities of the waves (counted positive in the negative $x$-direction, see figure 1) are, respectively

$$v_i = \frac{1}{Z_0} p_i(x) \qquad \text{... (4)}$$

$$v_r(x) = -\frac{1}{Z_0} p_r(x) \qquad \text{... (5)}$$

The field impedance (in the negative $x$-direction) in the standing wave is

$$Z(x) = \frac{p_i(x) + p_r(x)}{v_i(x) + v_r(x)} = Z_0 \frac{p_i(x) + p_r(x)}{p_i(x) - p_r(x)} \qquad \text{... (6)}$$

## 5.3 Inter-relationships

At the reference plane $x = 0$, therefore

$$Z = Z(0) = Z_0 \frac{1+r}{1-r} \qquad \text{... (7)}$$

from which follows

$$r = \frac{(Z/Z_0) - 1}{(Z/Z_0) + 1} \qquad \text{... (8)}$$

The sound absorption coefficient $\alpha$ for plane waves is

$$\alpha = 1 - |r|^2 \qquad \text{... (9)}$$

where $|...|$ indicates the magnitude of a complex quantity.

Equations (7) to (9) are the inter-relationships between the quantities which are determined according to this part of ISO 10534. If the reference plane is in the surface of a flat test object, these quantities are the surface impedance, the reflection factor (for normal sound incidence) and the absorption coefficient (for normal sound incidence) of the test object, respectively. If the reference plane is in front of the test object ($x > 0$), the absorption coefficient remains unchanged; the reflection factor $r$ and the impedance $Z$ will change to quantities which are said to be "transformed to a distance", namely the distance between the reference plane and the object surface. This concept is used sometimes in connection with structured test objects (see 9.1 and clause 10).

## 5.4 Standing wave

A pressure maximum in the standing wave occurs when $p_i$ and $p_r$ are in phase, i.e.

$$|p_{max}| = |p_0| \cdot (1 + |r|) \qquad \text{... (10)}$$

A pressure minimum occurs when they are in opposite phases

$$|p_{min}| = |p_0| \cdot (1 - |r|) \qquad \text{... (11)}$$

Using the standing wave ratio

$$s = |p_{max}| / |p_{min}| \qquad \text{... (12)}$$

then

$$s = \frac{1+|r|}{1-|r|} \quad \text{and} \qquad \text{... (13)}$$

$$|r| = \frac{s-1}{s+1} \qquad \text{... (14)}$$

## 5.5 Sound absorption coefficient

The sound absorption coefficient then follows from equations (9), (12) and (14) with the measured amplitudes $|p_{max}|$ and $|p_{min}|$ at a given frequency.

If the sound pressure in the impedance tube is measured in a logarithmic scale (in decibels), and the difference in level between the pressure maximum and the pressure minimum is $\Delta L$ dB, then

$$s = 10^{\Delta L/20} \qquad \text{... (15)}$$

The sound absorption coefficient then follows from

$$\alpha = \frac{4 \times 10^{\Delta L/20}}{(10^{\Delta L/20} + 1)^2} \qquad \text{... (16)}$$

## 5.6 Reflection factor

The phase angle $\Phi$ of the complex reflection factor

$$r = |r| \cdot e^{j\Phi} \qquad \text{... (17)}$$

follows from the phase condition for a pressure minimum in the standing wave

$$\Phi + (2n - 1)\pi = 2k_0 x_{min,n} \qquad \text{... (18)}$$

for the $n^{th}$ minimum ($n = 1, 2,...$) in front of the reference plane (towards the sound source).

From this it follows that

$$\Phi = \pi \left( \frac{4x_{min,n}}{\lambda_0} - 2n + 1 \right) \qquad \text{... (19)}$$

and for the first minimum ($n$ = 1)

$$\Phi = \pi\left(\frac{4x_{\min,1}}{\lambda_0} - 1\right) \qquad \ldots (20)$$

The complex reflection factor is then

$$r = r' + jr'' \qquad \ldots (21)$$

$$r' = |r| \cdot \cos\Phi \qquad \ldots (22)$$

$$r'' = |r| \cdot \sin\Phi \qquad \ldots (23)$$

## 5.7 Impedance

From equation (7) one obtains the normalized impedance $z = Z/Z_0$:

$$z = z' + jz'' \qquad \ldots (24)$$

$$z' = \frac{1 - r'^2 - r''^2}{(1 - r')^2 + r''^2} \qquad \ldots (25)$$

$$z'' = \frac{2\,r''}{(1 - r')^2 + r''^2} \qquad \ldots (26)$$

## 5.8 Wavelength

The wavelength $\lambda_0$ at the frequency $f$ of the sound signal follows either from the equation

$$\lambda_0 = c_0/f \qquad \ldots (27)$$

where $c_0$ is the sound velocity (for the determination of $c_0$ see annex A), or from the distance between two pressure minima of the standing wave (with a rigid termination of the impedance tube) which are numbered $n$ and $m$, respectively [see equation (19)]

$$\lambda_0 = \frac{2}{n - m}\left(x_{\min,n} - x_{\min,m}\right) \qquad \ldots (28)$$

# 6 Test equipment

The test equipment consists of an impedance tube, a test-sample holder, a probe microphone, a device to move and position the probe microphone, signal-processing equipment for the microphone signal, a loudspeaker, a signal generator, possibly an absorber termination of the impedance tube, and a thermometer.

The test equipment shall be checked before use by a series of tests. These help to exclude error sources and to secure the minimum requirements. Procedures for these tests are given in annex B.

## 6.1 Impedance tube

### 6.1.1 Construction

The impedance tube shall be straight, with a constant cross-section (to within 0,2 %) and with rigid, smooth, non-porous walls without holes or slits in the test section. The walls shall be heavy and thick enough (preferably made from metal or, for tubes of larger cross-sections, from tight and smooth concrete) not to be excited to vibration by the sound signal, and not to show vibration resonances in the working frequency range of the tube. For metal walls, a thickness of about 5 % or about 10 % of the cross-dimension is recommended for circular or rectangular tubes, respectively. Tube walls made out of concrete shall be sealed by a smooth tight and highly adhesive finish. The same holds for tube walls made of wood. These should be re-inforced and damped by an external coating of steel or lead sheets.

The shape of the cross-section of the tube is arbitrary, in principle. Circular or rectangular cross-sections are recommended (if rectangular, then preferably square).

If rectangular tubes are composed from plates, care shall be taken that there are no slits in the corners (e.g. by sealing with adhesives or with a finish).

### 6.1.2 Working frequency range

The working frequency range ($f_l < f < f_u$) of an impedance tube is determined by its length and cross-dimension. In order to be able to explore two pressure minima even for unfavourable reflection phases, the length of the test section of the tube shall be $l \geqslant 3\lambda_0/4$ at the lower frequency limit $f_l$.

The loudspeaker will generally produce higher wave modes besides the plane wave. They will die out within a distance of about three tube diameters or three times the maximum lateral dimension of rectangular impedance tubes below the lower cut-off frequency of the first higher mode. Test objects with laterally varying acoustic qualities (e.g. resonators) will produce higher-mode contributions to the reflected wave.

The test section of the impedance tube shall avoid both ranges of possible higher modes. Thus the tube length $l$ between the front surface of the test object and the loudspeaker is related to the lower frequency limit $f_l$ of the working frequency range by the condition

$$l \geqslant 250/f + 3d \qquad \ldots (29)$$

where

$l$ is the length, in metres;

$f$ is the frequency, in hertz;

$d$ is the inside diameter (or the maximum side length), in metres.

The upper limit of the working frequency range, $f_u$, is given by the possible onset of propagating higher modes. The condition for $f_u$ is

$$d \leqslant 0{,}5\lambda_0 \qquad \ldots (30)$$

$$f_u \cdot d \leqslant 170 \qquad \ldots (31)$$

for rectangular tubes with $f_u$ in hertz and the maximum side length $d$ in metres; and

$$d \leqslant 0{,}58\lambda_0 \qquad \ldots (32)$$

$$f_u \cdot d \leqslant 200 \qquad \ldots (33)$$

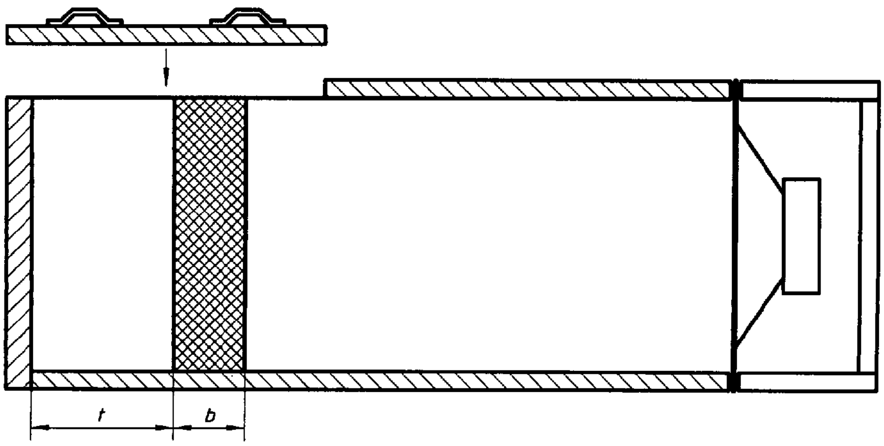
for circular tubes with the inside diameter $d$ in metres.

## 6.2 Test-sample holder

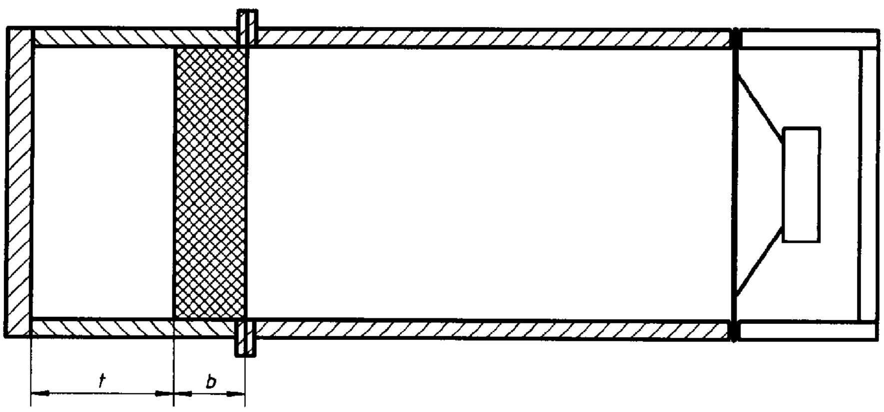
The sample holder is either integrated into the impedance tube or is a separate unit which, during the measurement, is tightly fixed to one end of the tube. (For possible arrangements, see figure 2.)

The length of the sample holder shall be large enough to install test objects leaving air spaces of a required depth behind them.

If the sample holder is a separate unit, its interior shape and dimensions shall conform to those of the impedance tube to within 0,2 %. The mounting of the tube shall be tight, without insertion of elastic gaskets (vaseline is recommended for sealing).




a) With removable cover




b) With a separate unit

**Figure 2 — Sample holder**

It is recommended to integrate the sample holder into the impedance tube and to make the installation section of the tube accessible by a removable cover in order to insert the test object. The contact surfaces of this removable cover with the tube shall be carefully finished and the use of a sealant (vaseline) is recommended to avoid small leaks. Generally, with rectangular tubes it is recommended to install the test object from the side into the tube (instead of pushing it axially into the tube); it is then possible to check the fitting and the position of the test object in the tube, to check the position and the flatness of the front surface, and to reposition the reference plane precisely in relation to the front surface. A sideways insertion also avoids the compression of soft materials.

The back plate of the sample holder shall be rigid and shall be fixed tightly to the tube since it serves as a rigid termination in many measurements. A metal plate of thickness not less than 2 cm is recommended.

For some tests a volume of air behind the test object, with a depth of $\lambda_0/4$, acts as a pressure-release termination. Movable plugs in the sample holder are used sometimes as rigid terminations, which allow for a variable depth of this air gap. They should be used with great care, because even tiny leaks between the plug and the wall of the sample holder will lead to erroneous results (for corrections for distances other than $\lambda_0/4$, see annex C).

## 6.3 Microphone

A movable microphone registers the standing wave pattern in the impedance tube, for the localization of pressure minima and for the acquisition of sound pressure amplitudes (or levels) in the maxima and minima of the standing wave.

Either the microphone moves outside the impedance tube, in which case it is connected to a probe tube with a sound pick-up opening in the impedance tube, or the microphone itself is placed (and is movable) in the impedance tube. The blockage of the cross-section of the impedance tube by the microphone and/or supports and/or other installations shall not be larger than 5 % in any cross-section of the test section.

### 6.3.1 Microphone with probe tube

The probe tube shall be of metal with sufficient wall thickness to avoid cross-talk of the sound field into the probe tube through the walls. The boring of the tube should be relative to its length; a long probe tube of small diameter may have too high an internal attenuation (for a check, see annex B). In a horizontal impedance tube, a centrally mounted probe tube shall be supported to avoid flexion of the probe tube, as this might give rise to higher sound modes. The supports shall not be close to the sound pick-up opening.

In a vertical impedance tube with the installation section at the lower end, the microphone or the probe tube may hang freely in the impedance tube.

In a rectangular impedance tube, the tube may be rotated around its axis by about 45° (see figure 3) and the probe placed into the lower corner; then any supports can be avoided. A further advantage of this position is that structure-borne vibrations of the

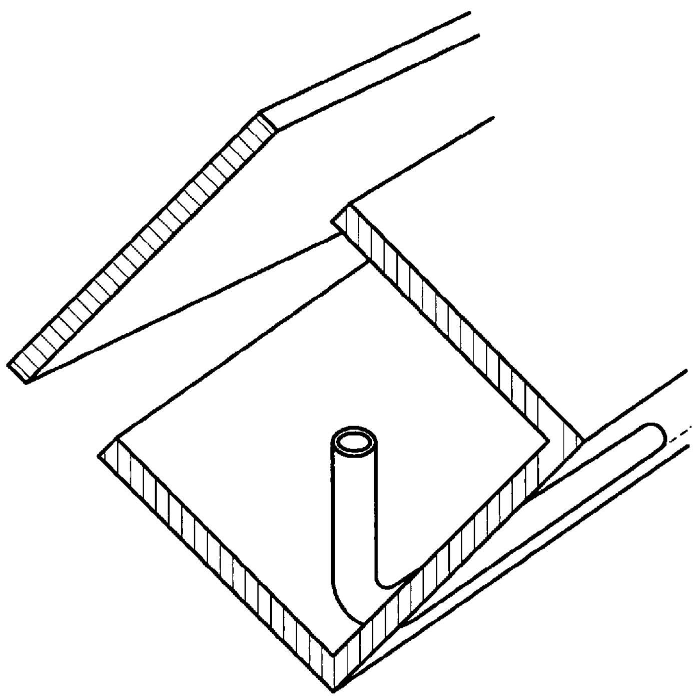


Figure 3 — Microphone probe tube in a corner of the impedance tube

impedance tube are smallest in the corners (see annex B for a check of structure-borne cross-talk). In principle, the sound pick-up opening can be in a corner, too. For registration of the sound pressure on or near the axis of the impedance tube, an elbow termination with the pick-up opening can be used.

Mechanical contacts between the probe and the impedance tube which can transmit vibrations to the probe tube shall be avoided, especially at the opening where the probe tube enters the impedance tube. At this opening, a soft foam support for the probe is recommended.

#### 6.3.2 Microphone in the impedance tube

For the maximum permissible blockage of the microphone and its supports, see 6.3. Structure-borne excitation of the microphone shall be avoided, because it is difficult to check for such bypass excitations.

#### 6.3.3 Acoustic centre of the probe microphone

The position of the acoustic centre of the pressure pick-up of the microphone or of the probe tube may be different from the geometrical centres. For the determination of the acoustic centre, see annex A.

### 6.4 Device for moving and positioning the microphone

The device for moving the probe microphone and for reading the position of its acoustic centre should allow for a precision of ± 0,5 mm. This tolerance may linearly increase for frequencies below 300 Hz down to 50 Hz, to a maximum tolerance of ± 2 mm. The positioning of the microphone shall be independent of the direction of motion of the microphone (no bias on reversal of direction).

A movable measuring rule which permits placing the rule on zero when the acoustic centre of the probe microphone is in the reference plane may be found to be convenient.

A device which allows continuous motion of the probe microphone at a constant speed is useful for the checks described in annex B.

### 6.5 Signal-processing equipment

The signal-processing equipment consists of an amplifier, a filter, a meter for the sound pressure or the sound pressure level (relative to an arbitrary but fixed reference pressure) and, preferably, a continuous recorder for the standing wave pattern.

The dynamic range of the signal-processing unit should be higher than 60 dB. The errors due to non-linearity, reading errors, instability and temperature sensitivity shall be less than 0,2 dB, or less than 2 % with a linear reading of the sound pressure. Sound level meters of class 0 normally fulfil the requirements.

There shall be sufficient filtering in the microphone circuit to ensure that noise and the harmonic content of the signal with the microphone or the probe at a pressure maximum are at least 50 dB below the fundamental frequency signal.

### 6.6 Loudspeaker

A membrane loudspeaker (or a pressure chamber loudspeaker for high frequencies with a horn as a transmission element to the impedance tube) should be the termination of the impedance tube at the end opposite to the sample holder. The surface of the loudspeaker membrane (or of the horn exit) shall cover at least two-thirds of the cross-sectional area of the impedance tube. The loudspeaker axis can be either coaxial with the tube [see figure 4 a)], or inclined [see figure 4 b)], or connected to the tube by an elbow [see figure 4 c)] to give space for the introduction of the probe tube.

The loudspeaker shall be contained in a sound-insulating box in order to avoid airborne cross-talk to the microphone. Elastic vibration insulation shall be applied between the impedance tube and the frame of the loudspeaker as well as to the loudspeaker box (preferably also between the impedance tube and the transmission element) in order to avoid structure-borne sound excitation of the impedance tube.

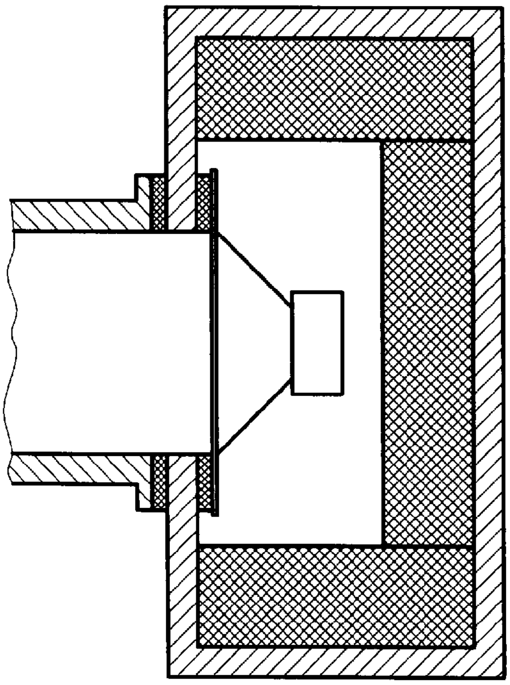
If more than one loudspeaker is used (e.g. for large tubes), then the phase of the loudspeakers should be checked in order to reduce the generation of higher modes.

### 6.7 Signal generator

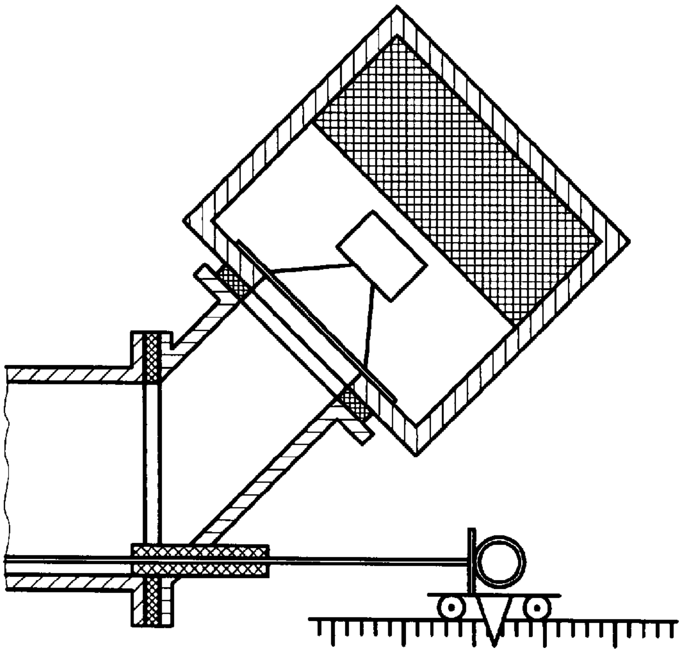
The signal generator consists of a generator for sinusoidal oscillations, a power amplifier and, possibly, a frequency counter.

The precision of frequency tuning and reading shall be better than 2 %. This is also the tolerance for uncontrolled frequency variations during a measurement.

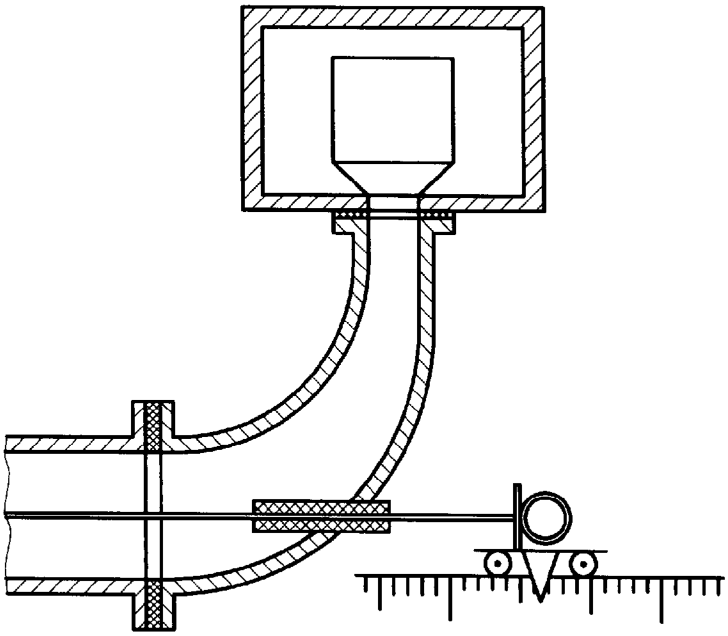
The generation of higher harmonics by the signal generator, the power amplifier and the loudspeaker shall be such that the harmonic content of the signal after filtering in the microphone circuit will not exceed the value specified in 6.5.



a) Straight loudspeaker termination



b) Termination with inclined loudspeaker with insertion of microphone probe tube



c) Loudspeaker connected to the tube with an elbow with insertion of microphone probe tube

**Figure 4 — Types of loudspeaker termination**

### 6.8 Loudspeaker termination

Resonances of the air column in the impedance tube may arise if the mechanical impedance of the loudspeaker membrane is high. They are an annoyance because the sound pressure level in the tube changes strongly with frequency. In that case one can apply a porous absorber coating inside the impedance tube in the area near to the loudspeaker.

### 6.9 Thermometer

The temperature in the impedance tube shall be measured and kept constant during a measurement with a tolerance of ± 1 K, because the speed of sound $c_0$ and the wavelength $\lambda_0$ are temperature dependent [see equation (A.5)].

## 7 Preliminary tests and measurements

The test equipment shall be checked before use by a series of tests. These help to exclude error sources and secure the minimum requirements. The checks shall be repeated after any modification to the equipment. They are described in annex B.

Another series of measurements can be performed as preliminary measurements before use of the equipment for material tests and after the checks mentioned above. They are all performed with a rigid termination of the empty impedance tube. Their aim is the determination of the acoustic centre of the probe microphone, the wavelength or the sound velocity in the impedance tube, and the corrections for the attenuation in the impedance tube. These preliminary measurements are described in annex A. They shall be repeated after any modification to the impedance tube or the probe microphone.

## 8 Mounting of the test sample

The impedance and absorption coefficient of a material can be affected quite strongly by mounting conditions, and these shall be carefully controlled and specified in order to obtain consistent results. The general requirements are that the test sample fit snugly in the holder, so that errors are not introduced by motion of the test sample as a whole when excited by the sound signal, or by absorption in, or shunting impedances due to, the crack around the edge. The test sample shall not be compressed unduly when mounted in the sample holder. Sealing the crack with vaseline or plasticine is recommended. The test sample can be held more firmly, if necessary, by greasing the entire edge.

The front surface of flat test samples shall be mounted normally to the tube axis. Their positions shall be specified with minimum tolerances, for objects with flat and smooth surfaces, within ± 0,5 mm. With porous materials of low bulk density, it may be helpful to fix and to define the surface by a thin, nonvibrating wire grid with a wide mesh.

At least two samples should be used in repeated measurements.

If the test object has a regular lateral structure (e.g. perforated cover sheets, resonator arrays, etc.), the test samples shall be cut out along lines of symmetry of that structure. If the dimensions of multiple structural units of the test object do not fit with the cross-dimensions of the impedance tube, the measurements shall be performed with several test samples cut at various positions relative to the structure. Repetition of the measurements with test samples cut from different parts of the test object are also necessary with materials which are laterally inhomogeneous (such as mineral fibre products).

## 9 Test methods

### 9.1 Specification of the reference plane

The first step in the measurement of the reflection factor and/or of the impedance after mounting of the test sample according to clause 8 is the specification of the reference plane ($x = 0$). It is usually the surface of the test object. If, however, the test object has a surface profile, the reference plane shall be placed at some distance in front of the test object. In a final step of the evaluation (see clause 10), the reflection factor and/or the impedance can be transformed by computation into a plane which is well defined by the structural criteria of the object.

For objects which have lateral structures, it is recommended to place the reference plane some distance in front of the test object, because lateral as well as profile structures will generate higher modes in the reflected wave.

The distances of the reference plane and the first minimum from the surface of the test object, which are used for evaluation in these cases, shall not be less than twice the tube diameter for circular tubes or the maximum lateral dimension for rectangular impedance tubes. Even with flat and apparently homogeneous test objects, it is recommended not to use minima which are positioned within this distance (spurious higher mode excitation; change of the acoustic centre of the probe on approximation to the object surface) for the evaluation.

For the computational transformation of the reflection factor and impedance from the reference plane back to the surface of the test object, see clause 10.

### 9.2 Specification of frequencies

The working frequency range shall be covered by frequencies with steps preferably not wider than one-third octave. Use frequencies at the centre frequencies of the one-third-octave bands in accordance with ISO 266 where possible. Other frequencies may be necessary for resonating test objects in order to reveal the resonances.

### 9.3 Determination of wavelength and attenuation

Before starting a measurement, determine the sound velocity $c_0$ in the tube in accordance with annex A, from which the wavelengths at the frequencies of measurement are obtained. This determination of $c_0$ shall be performed in the tube with rigid termination.

Determine the attenuation of the tube (i.e. $k_0''\lambda_0/4$) shall be performed in the same preliminary measurement in the tube with rigid termination in accordance with annex A.

The wavelength and the attenuation so determined for the measuring frequencies can be used for all later evaluations provided that neither the tube nor the temperature has been changed.

### 9.4 Selection of the signal amplitude

The signal amplitude shall be selected to be preferably more than 10 dB and at least 5 dB higher than the background noise in the deepest pressure minimum at that frequency.

### 9.5 Determination of the sound absorption coefficient

The standard procedure consists of measurement, at each frequency, of the amplitude $|p(x_{min,1})|$ and position $x_{min,1}$ of the first minimum, as well as of the amplitude $|p(x_{max,1})|$ of the first maximum. From these data compute

$$s_1 = |p(x_{max,1})|/|p(x_{min,1})|$$

and then find the magnitude $|r|$ of the reflection factor from equation (A.13) with $n = 1$. Finally obtain the absorption coefficient $\alpha$ from equation (9).

For survey measurements, $|p_{max}|$ and $|p_{min}|$ are measured at the first maximum and minimum, respectively, and then the sound absorption coefficient $\alpha$ is evaluated from equation (14).

### 9.6 Determination of the reflection factor

The standard procedure consists in measurement, at each frequency, of the amplitude $|p(x_{min,1})|$ and position $x_{min,1}$ of the first minimum, as well as of the amplitude $|p(x_{max,1})|$ of the first maximum.

From these data, compute

$$s_1 = |p(x_{max,1})|/|p(x_{min,1})|$$

then the magnitude $|r|$ of the reflection factor is evaluated from equation (A.12). Next, compute the phase $\Phi$ from equation (20) and, finally, obtain the real and imaginary components of the reflection factor from equations (22) and (23), keeping in mind that equation (20) gives the phase angle $\Phi$ in radians.

### 9.7 Determination of the impedance

Commence the procedure of measurement and evaluation as in 9.6 for the reflection factor, and then evaluate the normalized impedance $z$ from equations (24) to (26). In order to obtain the dimensioned impedance $Z$, multiply the result by the characteristic impedance $Z_0$. The value of $Z_0$ in pascal seconds per metre is obtained from

$$Z_0 = \rho_0 c_0 = 7\,064/\sqrt{T} \qquad (\text{Pa}\cdot\text{s})/\text{m} \qquad \ldots (34)$$

where $T$ is the temperature during the measurement, in kelvin.

### 9.8 Determination of the admittance

After determination of the impedance $Z$, the admittance $G = 1/Z$ follows from

$$G = G' + jG'' = \frac{Z' - jZ''}{Z'^2 + Z''^2} \qquad \ldots (35)$$

## 10 Transformation of reflection factor and impedance

The reflection factor $r$ and the impedance $Z$, according to the procedure described in clause 8, are determined for the reference plane $x = 0$. If, following 9.1, it is necessary to place the reference plane at a distance

$D$ in front of the surface of the test object, meaning that the object surface is positioned at $x = -D$, then the reflection factor $r$ and the impedance should be corrected for the distance $D$ in a final step.

The transformed reflection factor at any position $x$ is given by:

$$r(x) = p_r(x)/p_i(x) = r \cdot e^{-2jk_0x} = r\left[\cos(2k_0x) - j \cdot \sin(2k_0x)\right] \quad \ldots (36)$$

If $x = -D$, then the components of the reflection factor transformed to the object surface are

$$r(-D) = \left[r' \cdot \cos(2k_0D) - r'' \cdot \sin(2k_0D)\right] + j\left[r'' \cdot \cos(2k_0D) + r' \cdot \sin(2k_0D)\right] \quad \ldots (37)$$

The normalized impedance $z(x)$ which is corrected for the position $x$ from $x = 0$ where the normalized impedance is $z$ is obtained by

$$z(x) = \frac{Z(x)}{Z_0} = \frac{z \cdot \cos k_0x + j \cdot \sin k_0x}{\cos k_0x + j \cdot z \cdot \sin k_0x} \quad \ldots (38)$$

The normalized impedance at the object surface $x = -D$ is therefore

$$z(-D) = \frac{z'}{(\cos k_0D + z'' \cdot \sin k_0D)^2 + (z' \cdot \sin k_0D)^2} + \frac{j\left[z''\left(\cos^2 k_0D - \sin^2 k_0D\right) - \left(1 - z'^2 - z''^2\right)\sin k_0D \cdot \cos k_0D\right]}{(\cos k_0D + z'' \cdot \sin k_0D)^2 + (z' \cdot \sin k_0D)^2} \quad \ldots (39)$$

## 11 Test report

The test report shall contain the following items:

a) name of the test laboratory;

b) date of the test;

c) name of the producer and tradename of the test object, if it is a commercial product;

d) description of the test object including its acoustically relevant characteristics, i.e.

1) structural data such as

— lateral dimensions and total thickness,

— flatness of the surface or characteristic profile height, if any,

— number, arrangement and thickness of layers, including air spaces,

— dimensions of structural units, such as resonators, and their arrangement,

— positions of the cuts of the test sample relative to characteristic lines of test objects with lateral structures,

— structure, thickness and porosity of covers such as grids, and perforated metal sheet;

2) material data such as

— bulk density and, if available, air flow resistivity of porous materials,

— materials of the components of the test object;

3) construction characteristics such as

— connection of layers to each other (glued or other),

— partition walls normal to the surface in the test object;

e) mounting conditions of the test object in the tube;

f) number of test samples of the test object;

g) inner dimensions of the impedance tube and its shape;

h) material and thickness of the tube walls;

i) type of probe microphone (i.e. with or without probe tube);

j) maximum value and minimum value (in decibels) of the standing wave ratio in the test section and in the working frequency range from the tests in annex B;

k) distance of the reference plane from the surface of the test object, if larger than zero, and if so, indication whether the results are corrected to the object surface or not;

l) statement as to whether or not a correction for tube attenuation has been applied;

m) representation of the test results in tabular and/or in graphical form;

n) temperature and atmospheric pressure;

o) statement that the tests were performed in agreement with this part of ISO 10534, if this is true in all details.

If more than one test sample is tested for one test object, both the individual results for each test sample as well as the average shall be given. If different impedance tubes were used for a wider frequency range of tests, the working frequency ranges of the tubes shall overlap by about one octave. Test results from different impedance tubes shall not be averaged at the overlap frequencies but shall be given (and plotted) separately.

If the sound absorption coefficient is determined and represented in graphs over frequency, the abscissa shall be logarithmic with a scale of 100 mm per frequency decade, and the ordinate shall be linear with 100 mm for the range between 0 and 1, or otherwise in the same proportions as the coordinates (see ISO 354).

If the sound absorption coefficient $\alpha$ has values higher than 0,9, it is recommended to plot (on the same scale as $\alpha$) the magnitude $|r|$ of the reflection factor.

The reflection factor $r$ can either be represented by its components $r'$ and $r''$ or by its magnitude $|r|$ and phase $\Phi$. The unit for $\Phi$ (in degrees or radians) shall be indicated.

If impedances and/or admittances are determined, they shall preferably be represented as a normalized impedance ($z = Z/Z_0$) or as a normalized admittance ($g = GZ_0$).

If the results are presented in tabular form, the values for $\alpha$ shall be rounded to two significant figures, and the values for $z$ and $g$ shall be rounded to three significant figures.

# Annex A
(normative)

## Preliminary measurements

### A.1 Determination of the acoustic centre of the probe microphone

The position of sound pressure minima must be determined for the evaluation of equation (19) or (20) and equation (28). Since the acoustic centre of the pick-up opening of the probe tube or microphone may be different from their geometrical centres (especially with measurements of sound pressure minima), the acoustic centre of the probe microphone must be determined. This shall be performed at frequencies over all the working frequency range with mutual distances not larger than one-third octave and with the sample holder empty (rigid termination).

Then the pressure minima are at distances

$$x_{\min,n} = (2n - 1)\lambda_0/4 \quad (\text{with } n = 1, 2, \ldots) \qquad \ldots (A.1)$$

from the rigid back plate, which is assumed to be at $x = 0$ (see figure A.1). Let $y$ be the position of the geometrical centre of the probe and let $y = 0$ correspond to the position of the rigid termination. If $y_{\min,1}$ and $y_{\min,2}$ are the positions of the probe microphone (when positioned at the first and the second minima, respectively) then the correction $\delta$, by which the acoustic centre of the probe is to the left (see figure A.1) of the geometrical centre, is given by

$$\delta = \frac{1}{2}\left(3y_{\min,1} - y_{\min,2}\right) \qquad \ldots (A.2)$$

This correction shall be applied to all readings of $y_{\min,n}$ for the evaluation of equations (19) and (20):

$$x_{\min,n} = y_{\min,n} - \delta \qquad \ldots (A.3)$$

($\delta$ will be negative for an acoustic centre to the right).

### A.2 Determination of the wavelength

The determination of the wavelength in the impedance tube is preferably performed experimentally by an intermediate determination of the sound velocity $c_0$ in the impedance tube. Then the wavelength follows from equation (27). The determination of $c_0$ shall be performed with a rigid termination of the impedance tube at frequencies in steps of one-third octave over all the working frequency range.

For this, the wavelengths $\lambda_0(f)$ are determined from the positions of pressure minima $x_{\min,n}$ using equation (28). The sound velocity is then

$$c_0(f) = \lambda_0(f) \cdot f \qquad \ldots (A.4)$$

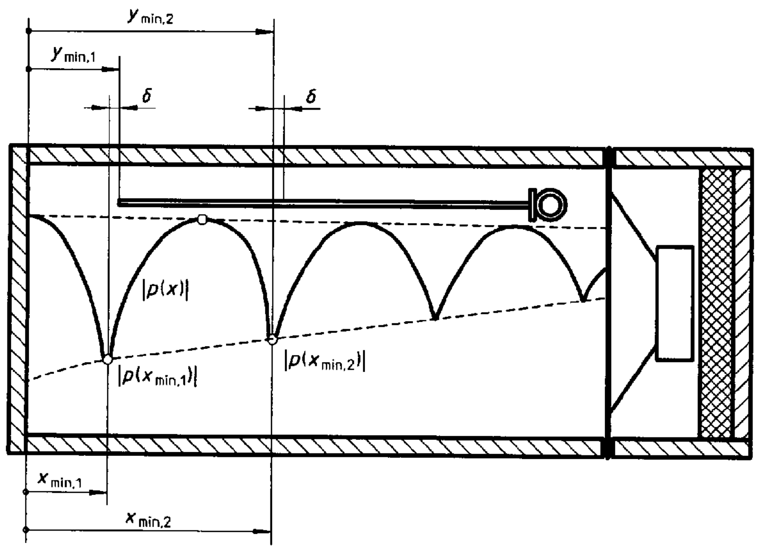



**Figure A.1 — Determination of the acoustic centre of the microphone**

The curve of these values, when plotted over the frequency, can be smoothed and interpolated. Slopes or peaks in this plot are indications of faults in the experimental set-up (leaks in the impedance tube, higher modes, irregular frequency and/or position readings, etc.).

If the determination of $c_0$ was performed at a temperature $T_0$ (in kelvin) in the impedance tube but the results are to be applied to measurements at which the temperature is $T$ (in kelvin), then the values shall be corrected for the temperature $T$ from

$$c_0(T) = c_0(T_0)\sqrt{T/T_0} \quad \text{. . . (A.5)}$$

The sound velocity at the test temperature can, alternatively, be determined from

$$c_0(T) = 343{,}30\sqrt{T/293} \quad \text{m/s} \quad \text{. . . (A.6)}$$

## A.3 Determination of corrections for the tube attenuation

The incident sound wave $p_i(x)$ and the reflected sound wave $p_r(x)$ will in general be attenuated during propagation due to viscous and thermal losses. The main effect of this attenuation is a monotonic increase in the amplitudes of the sound pressure minima $|p(x_{\text{min},n})|$ with increasing distance from the reflecting surface. Corrections shall be applied for this in the evaluation of quantities which are determined in accordance with this part of ISO 10534.

The attenuation can be described analytically by replacement of the real wave number $k_0$ by a complex wave number

$$k_0 = k_0' - j \cdot k_0'' \quad \text{. . . (A.7)}$$

$$k_0' = 2\pi/\lambda_0 \quad \text{. . . (A.8)}$$

where $k_0''$ is the attenuation in nepers per metre. The wavelength can still be determined from equation (27) or (28) if the attenuation is in a tolerable range (see B.1).

The amplitudes of the sound pressure minima $|p(x_{\text{min},n})|$ and of the sound pressure maxima $|p(x_{\text{max},n})|$ are then given by

$$\left|p(x_{\text{min},n})\right| = |p_0| \cdot \left| e^{k_0'' x_{\text{min},n}} - |r| \cdot e^{-k_0'' x_{\text{min},n}} \right| \quad \text{. . . (A.9)}$$

$$\left|p(x_{\text{max},n})\right| = |p_0| \cdot \left| e^{k_0'' x_{\text{max},n}} + |r| \cdot e^{-k_0'' x_{\text{max},n}} \right|$$

The numbering $n$ = 1, 2, 3, ... starts with the leftmost minimum to the right of the plane of reference and with the first maximum to the right of the minimum number 1.

Defining the standing wave ration $s_n$ of the $n^{\text{th}}$ minimum and the $n^{\text{th}}$ maximum ($n$ = 1, 2, 3, ...) by

$$s_n = \frac{\left|p(x_{\text{max},n})\right|}{\left|p(x_{\text{min},n})\right|} = \frac{e^{k_0'' x_{\text{max},n}} + |r| \cdot e^{-k_0'' x_{\text{max},n}}}{e^{k_0'' x_{\text{min},n}} - |r| \cdot e^{-k_0'' x_{\text{min},n}}} \quad \text{. . . (A.10)}$$

the magnitude of the reflection factor becomes

$$|r| = \frac{s_n \cdot e^{k_0'' x_{\text{min},n}} - e^{k_0'' x_{\text{max},n}}}{s_n \cdot e^{-k_0'' x_{\text{min},n}} + e^{-k_0'' x_{\text{max},n}}} \quad \text{. . . (A.11)}$$

Since

$$x_{\text{max},n} = x_{\text{min},n} + \lambda_0/4 \quad \text{. . . (A.12)}$$

the magnitude of the reflection factor in its final form is

$$|r| = e^{2k_0'' x_{\text{min},n}} \left( \frac{s_n - e^{k_0'' \lambda_0/4}}{s_n + e^{-k_0'' \lambda_0/4}} \right) \quad \text{. . . (A.13)}$$

Writing

$$k_0'' x_{\text{min},n} = 4\left(k_0'' \lambda_0/4\right)\left(x_{\text{min},n}/\lambda_0\right) \quad \text{. . . (A.14)}$$

it is recognized that the quantity $k_0''\lambda_0/4$ is needed for the correction. This quantity is determined in the empty tube with a rigid termination, $|r|$ = 1.

Then

$$\left|p(x_{\text{min},n})\right| = 2\,|p_0| \cdot \sinh\left(k_0'' x_{\text{min},n}\right) \quad \text{. . . (A.15)}$$

$$\left|p(x_{\text{max},n})\right| = 2\,|p_0| \cdot \cosh\left(k_0'' x_{\text{max},n}\right) \quad \text{. . . (A.16)}$$

If the pressure amplitudes are measured in the minima numbered $n$ and $n$ + 1 as well as in the maximum number $n$ between them, and if the quantity $\Delta_n$ is defined as

$$\Delta_n = \frac{\left|p(x_{\text{min},n+1})\right| - \left|p(x_{\text{min},n})\right|}{\left|p(x_{\text{max},n})\right|} \quad \text{. . . (A.17)}$$

then

$$\Delta_n = 2\sinh\left(k_0''\lambda_0/4\right) \qquad \text{... (A.18)}$$

and hence

$$\frac{k_0''\lambda_0}{4} = \operatorname{arcsinh}\frac{\Delta_n}{2} = \ln\left[\frac{\Delta_n}{2} + \sqrt{\frac{\Delta_n^2}{4}+1}\right] \qquad \text{... (A.19)}$$

which is the required exponent, and for the exponential factor

$$e^{\pm\frac{k_0''\lambda_0}{4}} = \left(\frac{\Delta_n}{2} + \sqrt{\frac{\Delta_n^2}{4}+1}\right)^{\pm 1} \qquad \text{... (A.20)}$$

The phase $\Phi$ of the reflection factor is still determined from equation (19) or (20).

The attenuation constant $k_0''$ of the tube shall be determined according to these formulae after each modification of the tube.

For small differences in level (less than 2 dB) between the first and second minima, and if $x_{min,1}/\lambda_0$ is not larger than 0,3, a correction for the attenuation can be derived by another, approximate, method. This method derives a corrected standing wave ratio $s_0$ by a straight extrapolation of the minima to the plane $x = 0$. In contrast to the method described above, this correction by extrapolation must be applied for each test object at each frequency.

The fictive amplitude $|p_0|$ of the first minimum, if it were at the object surface $x = 0$ (see figure A.2), can be approximated by first defining the corrected standing wave ratio $s_0$ by

$$s_0 = \frac{|p(x_{max,1})|}{|p_0|} \qquad \text{... (A.21)}$$

and then substituting for $s_0$ in this equation, taking $s_0$ from

$$\frac{1}{s_0} = \frac{1}{s_1} + \frac{2x_{min,1}}{\lambda_0}\left(\frac{1}{s_1} - \frac{1}{s_2}\right) \qquad \text{... (A.22)}$$

where $s_1$ and $s_2$ are the standing wave ratios of the first and the second minima, defined with the pressure maximum $|p(x_{max,1})|$ between them. This corrected standing wave ratio $s_0$ shall be applied in equation (14) in place of $s$.

For survey measurements, and at the lower end of the working frequency range, if no two pressure minima can be explored with sufficient precision, the attenuation constant can be estimated numerically by:

$$k_0'' = 1{,}94 \times 10^{-2}\left(\sqrt{f}/c_0 \cdot d\right) \qquad \text{... (A.23)}$$

where

- $d$ is the diameter, in metres, for a circular tube or the ratio of four times the cross-sectional area to the perimeter for a rectangular tube;
- $f$ is the frequency, in hertz.

This estimation, however, does not consider sources of attenuation such as porous walls and objects in the tube. Thus it can be considered as a lower limit.

If one is not sure whether such additional contributions of attenuation do exist, it is recommended to determine the attenuation using equation (19) or (20) at mid and upper frequencies of the working frequency range, and to extrapolate to the lower frequencies.

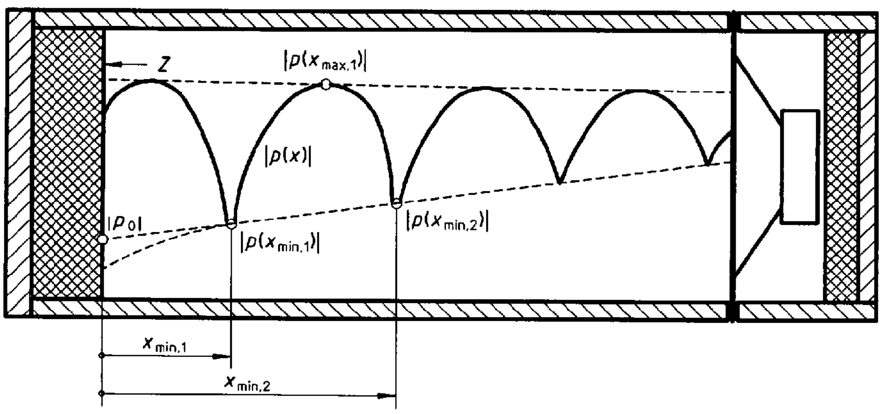



**Figure A.2 — Correction for test tube attenuation**

# Annex B
(normative)

# Verification of the test equipment

## B.1 Verification of the standing wave ratio

The standing wave patterns in the impedance tube shall be recorded (preferably by a slow continuous movement of the probe microphone through the test section) with an empty sample holder (rigid termination by the back plate of the sample holder). The recordings shall be repeated at frequencies in the working frequency range with frequency steps not larger than one-third octave. Intermediate frequencies shall be added if strong variations of the recorded patterns are observed for adjacent one-third-octave frequencies.

The standing wave ratios of the recorded patterns shall not be less than 45 dB (this allows for measurements of absorption coefficient $\alpha$ as low as 0,04). The envelope of the pressure minima shall be either horizontal or have a monotonic increase towards the loudspeaker end of the impedance tube (see figure B.1). An increase between succeeding minima of 1 dB is permissible (its influence on the measuring results can be corrected for; see annex A). There shall be no ripples on the standing wave patterns (see figure B.2).

If these requirements are not fulfilled, the reasons may be as follows.

a) There is too strong an increase in the lower envelope with standing wave ratios which are too small.

   Reason: too large an attenuation in the impedance tube (rough, porous, vibrating walls, leaks in the corners, cables and ropes in the test section).

b) The standing wave ratios are too small.

   Reasons: — the signal processing equipment has too small a dynamic range (electronic and/or acoustic noise, too high an attenuation in the probe tube);

   — airborne or structure-borne cross-talk (insufficient insulation of the loudspeaker, vibrations of the probe tube).

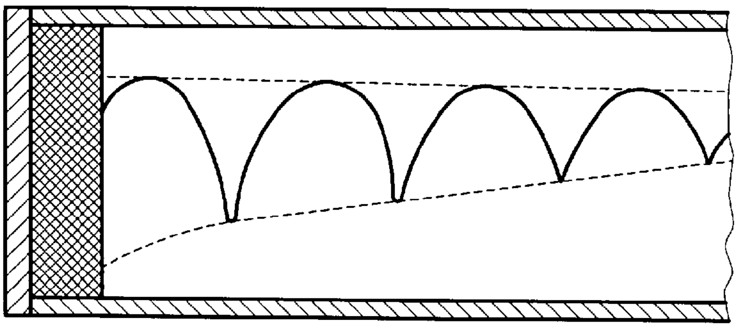


**Figure B.1 — Regular standing wave pattern with test tube attenuation**

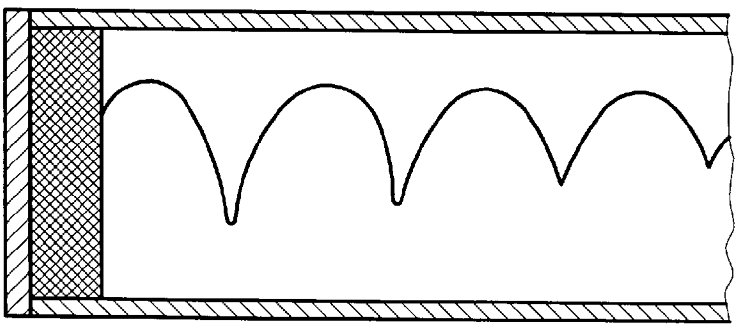


**Figure B.2 — Ripples on the standing wave pattern**

c) There is a non-monotonic increase of the lower envelope (see figure B.3).

Reasons: — higher modes in the test section (too strong an excitation of higher modes by the loudspeaker; higher modes generated by the probe tube or the microphone or the supports or other objects in the test section; vibrating tube walls; leaks in the tube walls);

— structure-borne sound in the impedance tube and/or in the probe tube.

d) There are ripples on the standing wave patterns.

Reason: higher harmonics in the signal (insufficient filtering; nonlinearity of a signal-generating component; rattling of an object in the test section, such as the probe tube or supports).

e) The minima are rounded off.

Reason: signal in the minima is below electronic or acoustic noise level (too high an attenuation in the probe tube; too small a signal amplitude, etc.).

Several phenomena and reasons may be combined. Resonant excitation to vibrations of the probe tube usually not only depends on the frequency but also on the position of the probe.

## B.2 Dynamic range of the probe microphone

In a first check the (electronic and acoustic) background noise levels shall be determined at the same frequencies as in B.1 with the signal switched off. If a continuously moving microphone is used in the measurements, these checks shall be performed with the moving microphone.

In a second check the sound pick-up opening of the probe tube shall be sealed and the checks of B.1 repeated at the same frequencies, but with the signal switched on with the same amplitude as in B.1.

The signal received in B.1 shall be at least 5 dB higher than the signal in the second check for all frequencies and probe microphone positions, and it shall be at least 10 dB higher than the background noise level, in the first check.

If the second requirement is not fulfilled, use higher signal amplitudes (avoiding electronic and acoustic nonlinearities) and/or more effective filtering. If the first requirement is not fulfilled, check whether the probe tube attenuation is too high (wider probe tube), whether there are vibrations on the impedance tube and/or on the probe tube (better vibration insulation) and whether there is airborne cross-talk (better insulation of the loudspeaker).

## B.3 Check of structure-borne excitation of the tube

After the direct structure-borne excitation of the probe microphone has been checked (and eliminated) by the tests given in B.2, and if the standing wave ratio found in B.1 is less than 45 dB, the structure-borne excitation of the impedance tube may be responsible for its insufficient performance.

For a check of this, install a plug of mineral fibre absorber material of length about 0,5 m to 1 m (bulk density not less than about 20 kg/m³ and not more than about 100 kg/m³) in the impedance tube at the limit of the test section towards the loudspeaker. Cover this plug on both sides by cover plates with a mass per unit area of not less than about 20 kg/m². The cover plates shall be mounted in the tube without direct mechanical contact with the tube walls and shall be sealed (e.g. with plasticine) around their edges. Introduce the microphone (probe) into the impedance tube through the test sample section. Record sound pressure levels for the frequencies used in the tests in B.1 (with the same loudspeaker amplitudes) with the probe microphone moving along the free section of the impedance tube.

The sound pressure levels so recorded shall be lower than the levels at the minima found in the tests of B.1. If the levels at the pressure minima in the present check agree with those from B.1, the vibration isolation between the loudspeaker and the impedance tube shall be improved.

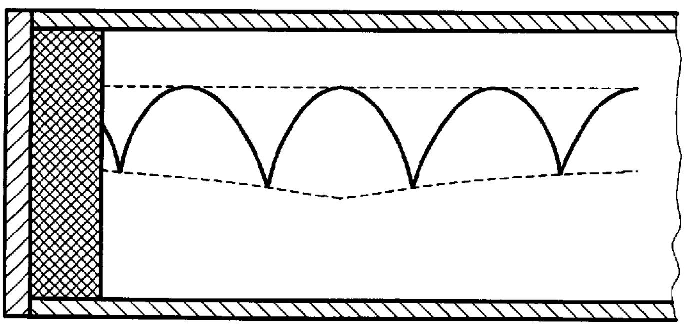


**Figure B.3 — Irregular standing wave pattern due to superposition of higher modes**

# Annex C
(normative)

## Pressure-release termination of test sample

**C.1** Sometimes a pressure-release termination of a test object is required. This pressure-release termination can be realized by an air gap between the rear surface of the test sample and the rigid termination of the sample holder. The depth of the gap shall be exactly $\lambda_0/4$ for the test frequency (with the sound velocity in the tube taken into account). Therefore, the depth of the air gap shall be carefully adapted for each frequency. For this reason, movable rigid plugs are sometimes used as rigid terminations of the sample holder. These movable plugs, however, quite often show small leaks at their edges so they are no longer acoustically rigid, and the error introduced by this cannot be taken into account quantitatively.

The reason for the use of pressure-release terminations is often the determination of the complex characteristic impedance $Z_a$ and the complex characteristic propagation constant $\Gamma_a$ of homogeneous absorber materials such as mineral fibre or foam.

If the layer of this material which is used in the tests has a thickness $b$, and if the surface impedance of this layer is $Z_r$ (rigid) if the termination is rigid, and if the surface impedance of the layer is $Z_s$ (soft) if the termination is pressure releasing, then the characteristic impedance and propagation constant of the absorber material are given by:

$$Z_a = \sqrt{Z_r Z_s} \qquad \text{... (C.1)}$$

$$\Gamma_a = \frac{1}{b} \cdot \operatorname{arctanh} \sqrt{\frac{Z_s}{Z_r}} \qquad \text{... (C.2)}$$

**C.2** The problem of a zero load impedance can be avoided by using another method. The depth $t$ of the air gap need not be exactly $\lambda_0/4$, but should be close to this value (see figure 2). Then the load impedance of the rear side of the absorber layer is

$$Z_1 = -jZ_0 \cdot \cot k_0 t \qquad \text{... (C.3)}$$

and the characteristic data of the absorber material are obtained from

$$Z_a = \sqrt{Z_r Z_s + Z_1(Z_s - Z_r)} \qquad \text{... (C.4)}$$

$$\Gamma_a = \frac{1}{b} \cdot \operatorname{arctanh} \frac{Z_a}{Z_r} \qquad \text{... (C.5)}$$

where $Z_r$ is the surface impedance for rigid termination and $Z_s$ is the surface impedance with the air gap, as in C.1. The second term under the root indicates the error which is introduced into the first method by a load impedance $Z_1$ which is not exactly zero. It may become quite large.

In practical applications of the second method, a given depth $t$ of the air gap shall be applied for all those frequencies for which it is approximately an odd multiple of $\lambda_0/4$ and for frequencies which are (about) one-third octave distant on both sides. Hence the whole frequency range can be covered with only a few settings of the depth $t$. This depth, the sound speed and the frequency should be determined as precisely as possible.

The thickness $b$ of the absorber layer in such measurements of the characteristic constants of the absorber material shall not be too small (three to four times the tube diameter), otherwise the test sample may be excited to vibrations as a whole, and reading errors of $b$ may become relatively large.

# Annex D
(informative)

## Determination of diffuse sound absorption coefficient $\alpha_{st}$ of locally reacting absorbers

The sound absorption coefficient $\alpha_{st}$ for diffuse (i.e. omnidirectional) sound incidence can be computed for absorbers of the "locally reacting" type (i.e. without sound propagation inside the absorber parallel to its surface) from the normalized impedance $z = z' + j \cdot z''$ which is determined in accordance with this part of ISO 10534.

The relationship is

$$\alpha_{st} = 8 \cdot \frac{z'}{z'^2 + z''^2} \left[ 1 - \frac{z'}{z'^2 + z''^2} \cdot \ln\left(1 + 2z' + z'^2 + z''^2\right) + \frac{1}{z''} \cdot \frac{z'^2 - z''^2}{z'^2 + z''^2} \cdot \arctan \frac{z''}{1 + z'} \right] \quad \text{... (D.1)}$$

If $z'' = 0$, then the last term in the square brackets will be $1/(1 + z')$. The maximum value of $\alpha_{st}$ which can be obtained from this formula is 0,96.

Similar explicit analytical relationships do not exist for bulk reacting absorbers (absorbers with inside sound propagation parallel to the surface, such as low-density open-cellular foams or mineral fibre absorbers).

**ICS 17.140.01**

**Descriptors:** acoustics, acoustic absorption, sound absorbers, tests, acoustic tests, determination, sound absorption coefficient, acoustic measurements.

Price based on 20 pages