Akustik – Bestämning av ljudabsorptionsfaktor och impedans i impedansrör –
Del 1: Metod med stående våg
(ISO 10534-1:1996)

Acoustics – Determination of sound absorption coefficient and impedance in impedances tubes –
Part 1: Method using standing wave ratio
(ISO 10534-1:1996)


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Foreword

The text of the International Standard from Technical Committee ISO/TC 43 "Acoustics" of the International Organization for Standardization (ISO) has been taken over as an European Standard by Technical Committee CEN/TC 126 "Acoustic properties of building products and of buildings", the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by December 2001, and conflicting national standards shall be withdrawn at the latest by December 2001.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Endorsement notice

The text of the International Standard ISO 10534-1:1996 has been approved by CEN as a European Standard without any modification.
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.
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, $Z(\mathbf{x})$: Ratio of the sound pressure $p(\mathbf{x})$ to the particle velocity $v(\mathbf{x})$ (directed into the test object) at a point $\mathbf{x}$ 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 $v$:

$$Z_r = \frac{p}{v}$$

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, $G_0$: 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 $Z_0$:

$$z = \frac{Z}{Z_0}$$

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, $|p_{\text{max}}|$, to that at an adjacent pressure minimum, $|p_{\text{min}}|$ (if necessary after correction for varying values at the minima due to sound attenuation in the impedance tube):

$$s = \frac{|p_{\text{max}}|}{|p_{\text{min}}|}$$

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

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

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

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

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

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

---

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 a logarithmic scale) of the sound pressure amplitudes \( |p(x_{\text{min}})| \) at pressure minima (one or more), and \( |p(x_{\text{max}})| \) at pressure maxima. These data are sufficient to determine the sound absorption coefficient. In addition, the distance \( x_{\text{min},1} \) 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)

\[
p_i(x) = p_0 e^{j\omega x} \quad \ldots (1)
\]

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

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

\[ v_i = \frac{1}{Z_0} p_i(x) \]  \hspace{1cm} \ldots (4)

\[ v_i(x) = -\frac{1}{Z_0} p_i(x) \]  \hspace{1cm} \ldots (5)

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

\[ Z(x) = \frac{p_i(x) + p_f(x)}{v_i(x) + v_f(x)} = Z_0 \frac{p_i(x) + p_f(x)}{p_i(x) - p_f(x)} \]  \hspace{1cm} \ldots (6)

### 5.3 Inter-relationships

At the reference plane \( x = 0 \), therefore

\[ Z = Z(0) = Z_0 \frac{1 + r}{1 - r} \]  \hspace{1cm} \ldots (7)

from which follows

\[ r = \frac{(Z / Z_0) - 1}{(Z / Z_0) + 1} \]  \hspace{1cm} \ldots (8)

The sound absorption coefficient \( \alpha \) for plane waves is

\[ \alpha = 1 - |r|^2 \]  \hspace{1cm} \ldots (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 \( p_f \) are in phase, i.e.

\[ |p_{\text{max}}| = |p_0|(1 + |r|) \]  \hspace{1cm} \ldots (10)

A pressure minimum occurs when they are in opposite phases

\[ |p_{\text{min}}| = |p_0|(1 - |r|) \]  \hspace{1cm} \ldots (11)

Using the standing wave ratio

\[ s = \frac{|p_{\text{max}}|}{|p_{\text{min}}|} \]  \hspace{1cm} \ldots (12)

then

\[ s = \frac{1 + |r|}{1 - |r|} \]  \hspace{1cm} \ldots (13)

\[ |r| = \frac{s - 1}{s + 1} \]  \hspace{1cm} \ldots (14)

### 5.5 Sound absorption coefficient

The sound absorption coefficient then follows from equations (9), (12) and (14) with the measured amplitudes \( |p_{\text{max}}| \) and \( |p_{\text{min}}| \) 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

\[ s = 10^{\Delta L/20} \]  \hspace{1cm} \ldots (15)

The sound absorption coefficient then follows from

\[ \alpha = \frac{4 \times 10^{\Delta L/20}}{(10^{\Delta L/20} + 1)^2} \]  \hspace{1cm} \ldots (16)

### 5.6 Reflection factor

The phase angle \( \Phi \) of the complex reflection factor

\[ r = |r| \cdot e^{i\Phi} \]  \hspace{1cm} \ldots (17)

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

\[ \Phi + (2n - 1)\pi = 2k_0x_{\text{min},n} \]  \hspace{1cm} \ldots (18)

for the \( n \)th minimum \( (n = 1, 2, \ldots) \) in front of the reference plane (towards the sound source).

From this it follows that

\[ \Phi = \pi \left( \frac{4x_{\text{min},n}}{\lambda_0} - 2n + 1 \right) \]  \hspace{1cm} \ldots (19)
and for the first minimum \( n = 1 \)

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

The complex reflection factor is then

\[
r = r' + jr'' \quad \ldots (21)
\]

\[
r' = |r| \cdot \cos \Phi \quad \ldots (22)
\]

\[
r'' = |r| \cdot \sin \Phi \quad \ldots (23)
\]

5.7 Impedance

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

\[
z = z' + jz'' \quad \ldots (24)
\]

\[
z' = \frac{1 - r'^2 - r''^2}{(1 - r')^2 + r''^2} \quad \ldots (25)
\]

\[
z'' = \frac{2 r''}{(1 - r')^2 + r''^2} \quad \ldots (26)
\]

5.8 Wavelength

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

\[
\lambda_0 = c_0/f \quad \ldots (27)
\]

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)]

\[
\lambda_0 = \frac{2}{n-m} \left( x_{\min,n} - x_{\min,m} \right) \quad \ldots (28)
\]

6 Test equipment

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 rigid 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 reinforced 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 \( (f_i < f < f_o) \) 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 \( l \geq 3\lambda_0/4 \) at the lower frequency limit \( f_i \).

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

\[
l \geq 250f + 3d \quad \ldots (29)
\]

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

\[
d \leq 0.5\lambda_0 \quad \ldots (30)
\]

\[
f_u \cdot d \leq 170 \quad \ldots (31)
\]

for rectangular tubes with \( f_u \) in hertz and the maximum side length \( d \) in metres; and

\[
d \leq 0.58\lambda_0 \quad \ldots (32)
\]

\[
f_u \cdot d \leq 200 \quad \ldots (33)
\]

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).

![Figure 2 — Sample holder](image-url)