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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
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Contents

Page

Annexes

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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.

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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, α: 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

ρ_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

ω 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), Φ: Results from the representation of the complex reflection factor by magnitude and phase:

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

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

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

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

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

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[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 λ_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)

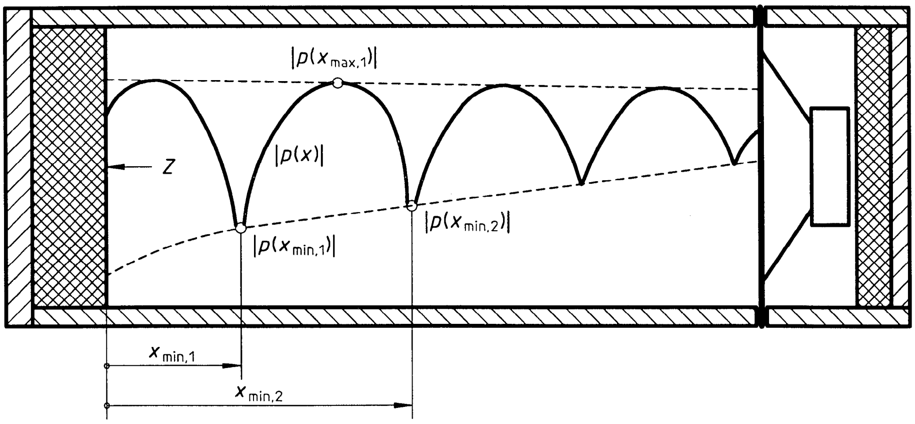
$$p_i(x) = p_0 e^{jk_0 x} \qquad \text{. . . (1)}$$

$$k_0 = \frac{\omega}{c_0} = \frac{2\pi f}{c_0} \qquad \text{. . . (2)}$$

where the amplitude p_0 is arbitrary.

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

$$p_r(x) = r \cdot p_0 \cdot e^{-jk_0 x} \qquad \text{. . . (3)}$$



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

$$v_{\mathrm{i}} = \frac{1}{Z_0} p_{\mathrm{i}}(x) \qquad \ldots (4)$$

$$v_{\mathrm{r}}(x) = -\frac{1}{Z_0} p_{\mathrm{r}}(x) \qquad \ldots (5)$$

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

$$Z(x) = \frac{p_{\mathrm{i}}(x) + p_{\mathrm{r}}(x)}{v_{\mathrm{i}}(x) + v_{\mathrm{r}}(x)} = Z_0 \frac{p_{\mathrm{i}}(x) + p_{\mathrm{r}}(x)}{p_{\mathrm{i}}(x) - p_{\mathrm{r}}(x)} \qquad \ldots (6)$$

5.3 Inter-relationships

At the reference plane $x = 0$, therefore

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

from which follows

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

The sound absorption coefficient α for plane waves is

$$\alpha = 1 - |r|^2 \qquad \ldots (9)$$

where $|\ldots|$ 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.

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

A pressure minimum occurs when they are in opposite phases

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

Using the standing wave ratio

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

then

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

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

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 ΔL dB, then

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

The sound absorption coefficient then follows from

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

5.6 Reflection factor

The phase angle Φ of the complex reflection factor

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

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

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

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

From this it follows that

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

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 λ_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

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

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

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

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

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

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

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

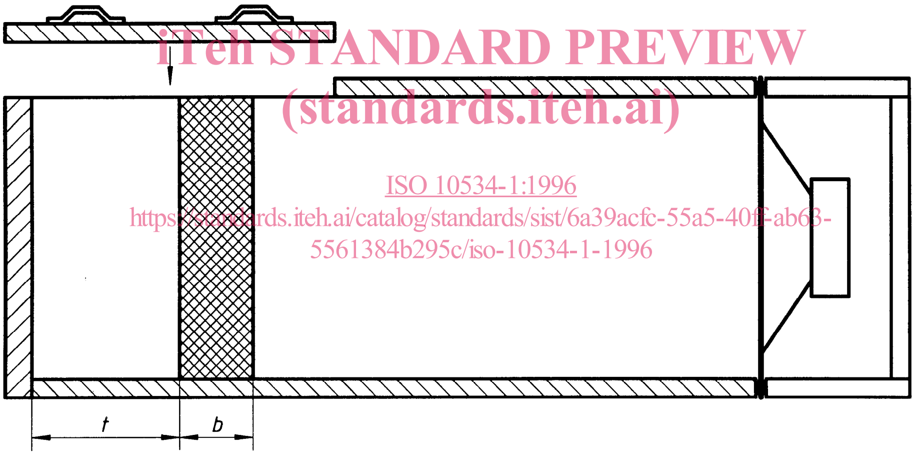
for circular tubes with the inside diameter d in metres.

6.2 Test-sample holder

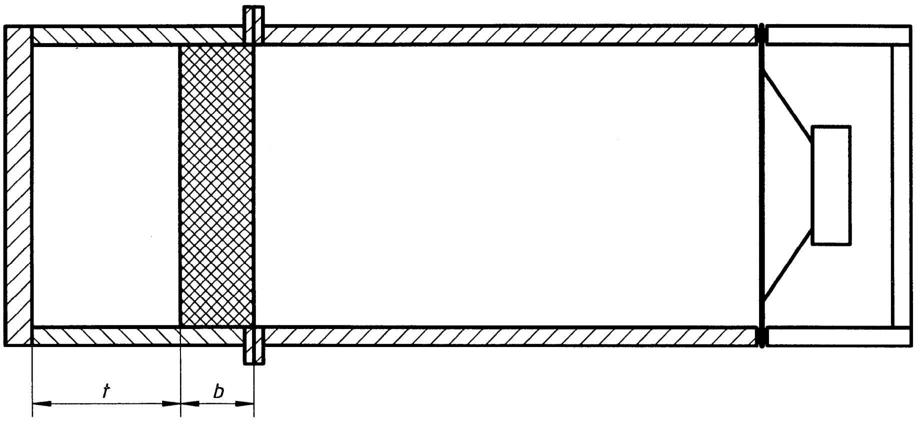
The sample holder is either integrated into the impedance tube or is a separate unit which, during the measurement, is tightly fixed to one end of the tube. (For possible arrangements, see figure 2.)

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

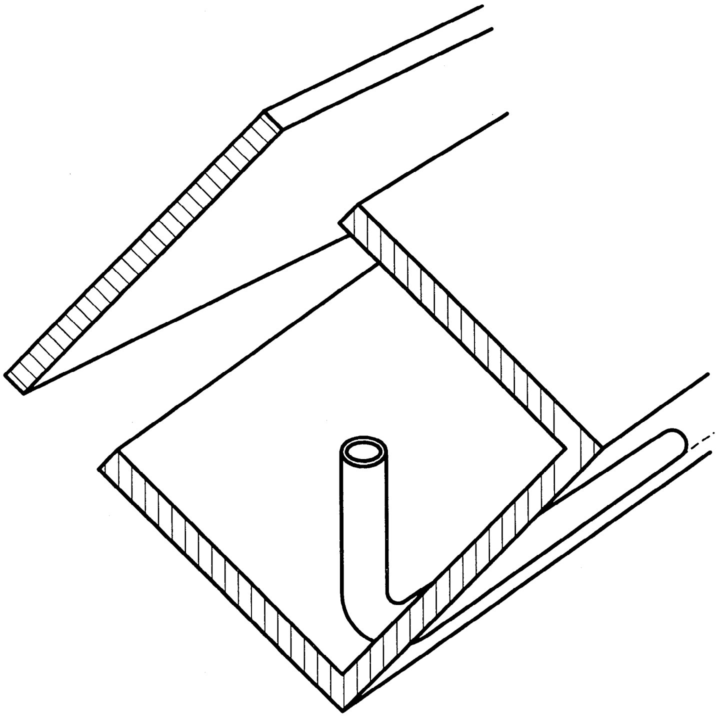


Figure 3 — Microphone probe tube in a corner of the impedance tube