INTERNATIONAL

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Standard Test Method for Impedance and Absorption of Acoustical Materials by Impedance Tube Method[1]

This standard is issued under the fixed designation C384; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the use of an impedance tube, alternatively called a standing wave apparatus, for the measurement of impedance ratios and the normal incidence sound absorption coefficients of acoustical materials.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C423 Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method

C634 Terminology Relating to Building and Environmental Acoustics

E548 Guide for General Criteria Used for Evaluating Laboratory Competence (Withdrawn 2002)[3]

2.2 *ANSI Standards:*

S1.6 Preferred Frequencies and Band Numbers for Acoustical Measurements[4]

3. Terminology

3.1 The acoustical terminology used in this test method is intended to be consistent with the definitions in Terminology C634. In particular, the terms "impedance ratio," "normal incidence sound absorption coefficient," and "specific normal acoustic impedance," appearing in the title and elsewhere in this test method refer to the following, respectively:

3.2 *Definitions:*

3.2.1 *impedance ratio, $z/\rho c \equiv r/\rho c + jx/\rho c$*; [dimensionless]—the ratio of the specific normal acoustic impedance at a surface to the characteristic impedance of the medium. The real and imaginary components are called, respectively, *resistance ratio* and *reactance ratio*. **C634**

3.2.2 *normal incidence sound absorption coefficient, α_n*; [dimensionless]—*of a surface, at a specified frequency*, the fraction of the perpendicularly incident sound power absorbed or otherwise not reflected. **C634**

3.2.3 *specific normal acoustic impedance, $z \equiv r + jx$*; [$ML^{-2}T^{-1}$]; mks rayl (Pa s/m)—*at a surface*, the complex quotient obtained when the sound pressure averaged over the surface is divided by the component of the particle velocity normal to the surface. The real and imaginary components of the specific normal acoustic impedance are called, respectively, *specific normal acoustic resistance* and *specific normal acoustic reactance*. **C634**

4. Summary of Test Method

4.1 A plane wave traveling in one direction down a tube is reflected back by the test specimen to produce a standing wave that can be explored with a microphone. The normal incidence sound absorption coefficient, α_n, is determined from the standing wave ratio at the face of the test specimen. To determine the impedance ratio, $z/\rho c$, a measurement of the position of the standing wave with reference to the face of the specimen is needed.

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[1] This test method is under the jurisdiction of ASTM Committee E33 on Building and Environmental Acoustics and is the direct responsibility of Subcommittee E33.01 on Sound Absorption.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

4.2 The normal incidence absorption coefficient and impedance ratio are functions of frequency. Measurements are made with pure tones at a number of frequencies chosen, unless there are compelling reasons to do otherwise, from those specified in ANSI S1.6.

5. Significance and Use

5.1 The acoustical impedance properties of a sound absorptive material are related to its physical properties, such as airflow resistance, porosity, elasticity, and density. As such, the measurements described in this test method are useful in basic research and product development of sound absorptive materials.

5.2 Normal incidence sound absorption coefficients are more useful than random incidence coefficients in certain situations. They are used, for example, to predict the effect of placing material in a small enclosed space, such as inside a machine.

5.3 Estimates of the random incidence or statistical absorption coefficients for materials can be obtained from normal incidence impedance data. For materials that are locally reacting, that is, without sound propagation inside the material parallel to its surface, statistical absorption coefficients can be estimated from specific normal acoustic impedance values using an expression derived by London (**1**).[5] Locally reacting materials include those with high internal losses parallel with the surface such as porous or fibrous materials of high density or materials that are backed by partitioned cavities such as a honeycomb core. Formulas for estimating random incidence sound absorption properties for both locally and bulk-reacting materials, as well as for multilayer systems with and without air spaces have also been developed (**2**).

6. Apparatus

6.1 The apparatus is essentially a tube with a test specimen at one end and a loudspeaker at the other. A probe microphone that can be moved along the length of the tube is used to explore the standing wave in the tube. The signal from the microphone is filtered, amplified, and recorded.

6.1.1 *Tube:*

6.1.1.1 *Construction*—The tube may be made of metal, plastic, portland cement, or other suitable material that has inherently low sound absorption properties. Its interior cross section may be circular or rectangular but must be uniform from end to end. The tube must be straight and its inside surface must be smooth, nonporous and free of dust to keep the sound attenuation with distance low. The interior of the tube may be sealed with paint, epoxy, or other coating material to ensure low sound absorption of the interior surface. The tube walls must be massive and rigid enough so that the propagation of sound energy through them by vibration is negligible.

6.1.1.2 *Diameter*—For circular tubes, the upper limit (**3**) of frequency is:

$$f < 0.586\ c/d \quad (1)$$

[5] The boldface numbers in parentheses refer to the list of references at the end of this standard.

where:

f = frequency, Hz,
c = speed of sound in the tube, m/s, and
d = diameter of tube, m.

For rectangular tubes, with d used as a symbol for the larger cross section dimension, the upper limit is:

$$f < 0.500\ c/d \quad (2)$$

It is best to work well below these limits whether the tube is circular or rectangular. At frequencies above these limits, cross modes may develop and the incident and reflected waves in the tube are not likely to be plane waves. If sound with a frequency below the limiting value enters the tube as a non-plane wave, it will become a plane wave after traveling a short distance. For this reason, no measurement should be made closer than one tube diameter to the source end of the tube.

6.1.1.3 *Length*—The length of the tube is also related to the frequencies at which measurements are made. The tube must be long enough to contain that part of the standing wave pattern needed for measurement. That is, it must be long enough to contain at least one and preferably two sound pressure minima. To ensure that at least two minima can be observed in the tube, its length should be such that:

$$f > 0.75\ c/(l - d) \quad (3)$$

where:

l = length of tube, m.

If, for example, the tube is 1 m in length and 0.1 m in diameter and the speed of sound is 343 m/s, the frequency should exceed 286 Hz if two sound pressure minima are to be observed.

6.1.2 *Test Specimen Holder*—The specimen holder, a detachable extension of the tube, must make an airtight fit with the end of the tube opposite the sound source. Provision must be made for containing the specimen with its face in a known position. The interior cross-sectional shape of the specimen holder must be the same as the tube itself. Provision must be made for backing the specimen with a metal backing plate that forms a seal with the interior of the specimen holder. A recommended backing is a solid steel plate with a thickness of not less than 2 cm. The sample holder may be constructed in such a way that a variable depth air space can be provided between the back of the test specimen and the surface of the metal backing plate. Provision must be made for substituting the metal backing plate for the specimen for calibration purposes.

6.1.3 *Sound Source:*

6.1.3.1 *Kind and Placement*—The sound source may be a loudspeaker or a horn-driver coupled to a short exponential horn. The source may face directly into the tube or, to avoid interference with the probe microphone, it may be placed to one side. Since the source diameter may be larger than the tube diameter, it is best to mount the source in an enclosure to which the tube is connected.

6.1.3.2 *Precautions*—Precautions should be taken to avoid direct transmission of vibration from the sound source to the probe microphone where it enters the tube or to the tube itself. Such vibrational transmission will be evidenced by a smaller standing wave ratio (higher normal incidence sound absorption) than would be expected for the material under test. Vibration isolation material, such as polymeric foam, may be placed between the sound source and tube or the microphone probe, or both, to minimize this effect. Interaction between the sound field within the tube and the loudspeaker diaphragm may cause the frequency response of the loudspeaker to be nonlinear. Although this has no effect on measurement accuracy, it does require awkward changes in amplifier gain settings when switching between test frequencies. This effect can be minimized by lining the interior of the tube near the sound source with a porous, absorbent material.

6.1.4 *Microphone*—If the microphone is small enough, it may be placed inside the impedance tube connected to a rod or other device that can be used to move it along the length of the tube. If the microphone is placed within the tube, the total cross-sectional area of the microphone and microphone supports shall be less than 5 % of the total cross-sectional area of the tube. In most applications, the microphone is on the outside connected to a hollow probe tube that is inserted through the source end of the apparatus and is aligned with the central axis of the tube. In principle, the sensing element of the microphone or of the microphone probe may be positioned anywhere within the tube cross-sectional area. In practice, the microphone or the end of the probe tube must be supported by a spider or other device to maintain its position on the central axis of the impedance tube or at a constant distance from the central axis.

6.1.5 *Microphone Position Indicator*—A scale shall be provided to measure the position of the microphone with respect to the specimen face. It is not necessary that zero on the scale correspond to the position of the specimen face. The resolution of this scale should be such that microphone position can be measured to the nearest 1.0 mm or, if a vernier is used, to the nearest 0.1 mm.

6.1.6 *Test Signal:*

6.1.6.1 *Frequency*—The test signal shall be provided by a sine wave oscillator generating a pure tone chosen from the list of preferred band center frequencies listed in ANSI S1.6. The test frequency shall be controlled to within ±1 % during the course of a measurement. If a digital frequency synthesizer is used, the test signal may be assumed to agree with the set point within the required ±1 %.

6.1.6.2 *Frequency Counter*—It may be necessary, and is usually advisable, to measure the frequency of the signal with an electronic counter rather than to rely on the calibration and indicated setting of the frequency generator. Frequency should be indicated to the nearest 1 Hz.

6.1.7 *Output-Measuring Equipment:*

6.1.7.1 *Filter*—The microphone output should be filtered to remove any harmonics and to reduce the adverse effect of ambient noise. The filter width must be no wider than one-third octave, but a one-tenth octave or narrower filter bandwidth is preferable.

6.1.7.2 *Amplifier*—The signal-to-noise ratio of the measuring amplifier must be at least 50 dB. The amplified signal may be read and recorded as a voltage or as a sound pressure level (dB). It is presumed in Sections 9 and 10 of this test method that voltages rather than dB levels are being used. As only pressure ratios are required for the computations in this test method, it is not necessary that the sound pressure measurement system be calibrated to a known, reference sound pressure level or to a known voltage.

6.1.8 *Temperature Indicator*—A thermometer or other ambient temperature sensing device shall be located in the vicinity of the impedance tube. This device should indicate air temperature inside the tube to within ±2 °C.

6.1.9 *Monitoring Oscilloscope*—While not required for any actual measurement purpose, it is recommended that an oscilloscope be used to monitor both the voltage driving the sound source and the output of the amplifier. Observing the oscilloscope trace is useful in locating the exact position of pressure minima within the tube as well as in detecting distortion, excess noise, and other possible problems in the voltage signals.

7. Sampling

7.1 At least three specimens, preferably more if the sample is not uniform, should be cut from the sample for the test. When the sample has a surface that is not uniform (for example a fissured acoustical tile), each specimen should be chosen to include, in proper proportion, the different kinds of surfaces existing in the larger sample.

8. Test Specimen Preparation and Mounting

8.1 The measured impedance properties can be strongly influenced by the specimen mounting conditions. Therefore, the following guidelines for the preparation and mounting of specimens are provided.

8.2 The specimen must have the same shape and area as the tube cross section, neither more nor less. The specimen must fit snugly into the specimen holder, fitting not so tightly that it bulges in the center, nor so loosely that there is a space between its edge and the holder. Movement of the specimen as a whole and spaces between the specimen perimeter and sample holder can result in anomalous values of normal incidence sound absorption. Specimen movement can be minimized by the use of thin, double-sided adhesive tape applied between the back of the specimen and the metal backing plate. Spaces at the specimen perimeter can be sealed with petroleum jelly.

8.3 The specimen must have a relatively flat surface since the reflected wave from a very uneven surface may not have become a plane wave at the position of the first minimum. If the specimen is an anechoic wedge, or an array of wedges, refer to Annex A1.

8.4 When the specimen has a very uneven back, a layer of putty-like material should be placed between it and the metal backing plate to seal the back of the specimen and to add enough thickness to make the back of the specimen parallel to the front. Otherwise, the unknown airspace may be the dominant factor in the measured results.

9. Description of Standing Wave Pattern in Tube

9.1 Fig. 1 represents microphone voltages that might be measured in a tube at various distances from the specimen face. That is, Fig. 1 is a standing wave pattern, in this case for a

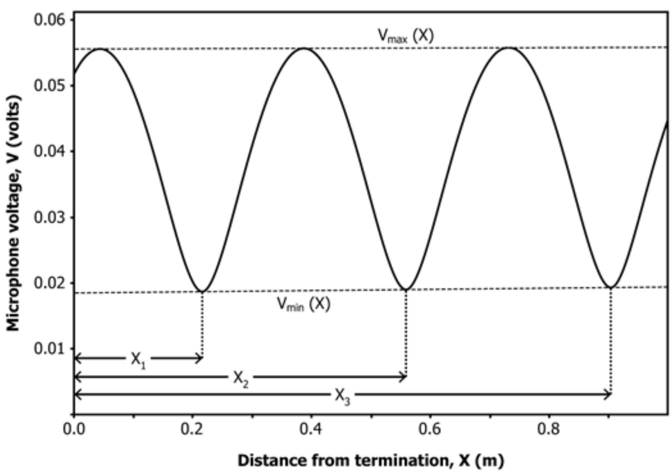

FIG. 1 Microphone Voltage in 1.0 m Tube Driven at 500 Hz

reflective specimen installed in a one-metre tube with the tube driven at 500 Hz. The minimum points at x_1, x_2, and x_3 on the standing wave pattern are spaced half a wavelength apart and positioned midway between the maxima. It should be noted that the data shown in Fig. 1 are plotted as voltage versus distance rather than voltage level (in dB) versus distance.

9.2 The standing wave pattern generally contains a finite number of discrete minima (for example, x_1, x_2, x_3 in Fig. 1) and the locus formed by these individual minimum microphone voltages defines a continuous $V_{min}(x)$ function as shown by the lower dotted line on Fig. 1. Similarly, the locus of maximum voltages can be used to define a continuous $V_{max}(x)$ function, shown as the upper dotted line on Fig. 1. A standing wave ratio, *SWR*, also a function of x, can be formed according to:

$$SWR(x) = V_{max}(x)/V_{min}(x) \tag{4}$$

where:

SWR(x) = standing wave ratio at location x, dimensionless.

Note that *SWR(x)* will be a positive, real number equal to or greater than one.

9.3 The various maxima of the standing wave pattern of Fig. 1 are nearly equal in magnitude. Thus $V_{max}(x)$ is very nearly a straight, horizontal line. The minimum microphone voltages, however, form a $V_{min}(x)$ locus with a noticeable slope. It is not the absorption at the sample face but rather the attenuation within the tube itself that causes $V_{min}(x)$ to exhibit this slope. Indeed, if there were no attenuation of incident and reflected waves as they propagated back and forth in the tube, $V_{min}(x)$ and $V_{max}(x)$ could both be represented as horizontal lines and *SWR(x)* would be the same everywhere along the length of the tube. Attenuation within the tube, however, while having only a slight effect on the individual maxima, causes the individual voltage minima to increase with increasing distance from the face of the specimen.

9.4 The primary purpose for making the measurements described in this test method is to find the standing wave ratio at the face of the specimen, that is, *SWR*(0). This determination must be done indirectly by extrapolation of the maximum and minimum microphone voltages actually measured in the tube. Section 10 of this test method describes several methods for performing the extrapolation depending on the number of maxima and minima observed.

9.5 *Tube Attenuation*—Losses within a tube can generally be described by:

$$p(x) = p_0 e^{-\zeta x} \tag{5}$$

where:

p_0 = the pressure at some reference position,
x = the absolute distance traveled by the wave from the reference position, and
ζ = the attenuation constant.

Kirchhoff (see Ref. 4) developed and Beranek (**5**) subsequently modified a formula for estimating the attenuation constant as:

$$\zeta = 0.02203 f^{1/2}/(cd) \tag{6}$$

where:

ζ = attenuation constant, m^{-1}.

For this purpose, the equivalent diameter of a tube with rectangular cross section is four times the area of the cross section divided by its perimeter.

10. Procedure

10.1 *Calculation of Velocity of Sound, c*—The velocity of sound in air is computed from the measured temperature according to:

$$c = 20.05\,(T + 273.1)^{1/2} \tag{7}$$

where:

T = air temperature, °C.

10.2 *Calculation of Wavelength*, λ—The wavelength of sound at each test frequency is computed from the speed of sound and the test frequency according to:

$$\lambda = c/f \tag{8}$$

where:

λ = wavelength, m.

10.3 *Correction Factor:*

10.3.1 To define the standing wave pattern within the tube, it is necessary to know the distance from the sample face at which each pressure is being measured. The exact location of the face of the mounted sample within the tube can be determined by gently advancing the probe until it makes contact with the sample face and noting the scale reading at the point of contact. The exact location of a measured pressure, however, requires applying a correction factor to the observed scale reading at the point where the pressure is measured. This is due to the fact that the acoustic center of a microphone or microphone probe does not necessarily correspond with its geometric center.

10.3.2 The correction factor is computed based on the assumption that, with a highly reflective metal backing plate mounted in the tube, a sound pressure minimum will occur at precisely λ/4 from the surface of the plate. For each test frequency the correction factor is thus determined with the metal backing plate in place as follows:

$$x_{cor} = (x_{1/4} - x_{mr}) - \lambda/4 \quad (9)$$

where:

x_{cor} = correction factor, m,
$x_{1/4}$ = observed scale reading with microphone probe at first minimum, m, and
x_{mr} = observed scale reading with probe touching face of metal backing plate, m.

10.3.3 During routine measurements with a specimen in place, all observed scale readings at a particular test frequency should be corrected by the scale calibration factor for that frequency as follows:

$$x = (x_{obs} - x_{sf}) - x_{cor} \quad (10)$$

where:

x = true distance from specimen surface, m,
x_{obs} = observed scale reading, m, and
x_{sf} = observed scale reading with probe touching specimen face, m.

If the absolute position of the scale on the test apparatus can be adjusted, it is convenient to use this adjustability to make x_{sf} in Eq 10 equal to zero.

10.3.4 During a protracted series of measurements, the air temperature in the impedance tube should be held constant to within ±5 °C to keep the variation in the velocity of sound to less than 1.0 %. If, during the course of a series of measurements, the air temperature varies outside of this range, a new set of scale correction factors should be determined and applied to the observed scale readings.

NOTE 1—The need to make corrections for temperature changes can be minimized if the measurement apparatus is located in a constant-temperature environment.

10.4 *Measurement of Standing Wave Pattern*—With a specimen mounted in the tube and the tube excited at a particular test frequency, adjust the voltage to the loudspeaker so that the microphone voltages at the minimums are at least 10 times greater than the background noise voltage (10 dB above the background noise). Note and record the temperature. Note and record the scale reading when the probe just touches the sample face. Move the microphone observing and recording the locations and microphone voltages of the various maxima and minima in the tube. Correct the observed locations in accordance with Eq 9 and Eq 10. The corrected data can be sketched in the manner of Fig. 1 to define the general shape of the standing wave pattern in the tube for this particular test frequency.

10.5 *Determination of Standing Wave Ratio at Specimen Face*—As discussed in Section 9, sound attenuation in the tube causes the locus of the sound pressure minima (and to a lesser extent the locus of the sound pressure maxima) to change with increasing distance from the specimen face. Thus, it is necessary to employ some type of extrapolation or estimation technique to determine the standing wave ratio, *SWR*(0), at the specimen face. The particular technique to use depends on the number of minima and maxima in the measured standing wave pattern.

10.5.1 *Two or More Minima Present*—When two or more minima are present, one or more maxima will be observed as well. If there is only one voltage maximum, it should be used as V_{max} (0). If there are two or more maxima, the maximum nearest (but not at) the sample face should be taken as $V_{max}(0)$. A linear extrapolation of voltage minima back to the sample face is used to find $V_{min}(0)$ according to:

$$V_{min}(0) = V(x_1) - x_1[V(x_2) - V(x_1)]/(x_2 - x_1) \quad (11)$$

10.5.2 *One Minimum and One Maximum Present*—When only one minimum and one maximum are observed, the single maximum voltage is taken to be $V_{max}(0)$. In this case, there is only one minimum, $V(x_1)$, and a graphical extrapolation back to the specimen face cannot be used. However, a valid approximation for the minimum voltage at the sample face in this case is given by:

$$V_{min}(0) = V(x_1) - \zeta x_1 V_{max}(0) \quad (12)$$

where: ζ is calculated from Eq 6.

10.5.3 *Only One Minimum and No Maximum Present*—When no actual maximum can be measured in the tube, it is not wise to try to measure the maximum level at the face of the specimen and use this value as a maximum. One reason for this is that only when the impedance phase angle is zero is the level at the sample face a maximum. Furthermore, if the microphone is too close to the specimen, the sound may be blocked and the measured sound pressure level will be less than maximum. In this situation, however, a maximum level may be inferred from a measurement of the sound pressure levels at λ/8 distance on either side of the minimum. The rationale for doing so is as follows:

10.5.3.1 The squared pressure at any position x in the tube may be written as:

$$p^2 = p_i^2 + p_r^2 + 2 p_i p_r \cos\gamma \quad (13)$$

where:

p_i = incident pressure, N/m^2,
p_r = reflected pressure, N/m^2, and
γ = phase angle between incident and reflected pressure waves, degrees.

If losses due to attenuation in the tube are neglected, the pressure at a standing wave maximum, where $\gamma = 0°$, will be given by:

$$p_{max}^2 = p_i^2 + p_r^2 + 2 p_i p_r \quad (14)$$

and at a standing wave minimum, where $\gamma = 180°$,

$$p_{min}^2 = p_i^2 + p_r^2 - 2 p_i p_r \quad (15)$$

At a distance of λ/8 on either side of a minimum, where $\gamma = 90°$,

$$p_{\lambda/8}^2 = p_i^2 + p_r^2 \quad (16)$$

It follows that:

$$p_{\lambda/8}^2 = 0.5(p_{max}^2 + p_{min}^2) \quad (17)$$

Since the measured microphone voltage is indicative of the sound pressure, this last result can be rewritten and rearranged to give:

$$V_{max} = (2V_{\lambda/8}^2 - V_{min}^2)^{1/2} \quad (18)$$