Designation: ~~E2611 – 09~~ E2611 – 17

Standard Test Method for

~~Measurement of~~ Normal Incidence ~~Sound Transmission of Acoustical Materials~~ Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method[1]

This standard is issued under the fixed designation E2611; 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 a tube, four microphones, and a digital frequency analysis system for the measurement of normal incident transmission loss and other important acoustic properties of materials by determination of the acoustic transfer matrix.

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 and health 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]
C634 Terminology Relating to Building and Environmental Acoustics
E90 Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements
E1050 Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones and a Digital Frequency Analysis System
2.2 *ISO Standards:*
ISO 140-3 Acoustics—Measurement of Sound Insulation in Buildings and of Building Elements—Part 3: Laboratory Measurement of Airborne Sound Insulation of Building Elements[3]

3. Terminology

3.1 *Definitions*—The acoustical terminology used in this test method is intended to be consistent with the definitions in Terminology C634.

3.1.1 *reference plane*—an arbitrary section, perpendicular to the longitudinal axis of the tube that is used for the origin of linear dimensions. Often it is the upstream (closest to the sound source) face of the specimen but, when specimen surfaces are irregular, it may be any convenient plane near the specimen.

3.1.2 *sound transmission coefficient, τ*—(dimensionless) of a material in a specified frequency band, the fraction of airborne sound power incident on a material that is transmitted by the material and radiated on the other side.

$$\tau = \frac{W_t}{W_i}$$

where:

W_t and W_i = the transmitted and incident sound power.

3.1.3 *sound transmission loss, TL*—of a material in a specified frequency band, ten times the common logarithm of the reciprocal of the sound transmission coefficient. The quantity so obtained is expressed in decibels.

$$TL = 10 \log_{10}\left(\frac{W_i}{W_t}\right) = 10 \log_{10}\left(\frac{1}{\tau}\right)$$

3.1.3.1 *Discussion*—

In this standard the symbol TL_n will be applied to sound which impinges at an angle normal to the test specimen, as opposed to an arbitrary or random angle of incidence.

3.2 *Symbols:*

c = speed of sound, m/s.

ρ = density of air, kg/m^3.

f = frequency, hertz, (Hz).

G_{11}, G_{22}, etc. = auto power spectra (autospectrum) of the acoustic pressure signal at microphone locations 1, 2, and so on.

G_{21}, G_{32}, etc. = cross power spectrum (cross spectrum) of the acoustic pressure signals at location 2 relative to location 1, 3 relative to 1, and so on. In general, a complex value.

H^-_{21}, H^-_{31}, etc. = measured transfer function of the acoustic pressure signals at location 2 relative to location 1, 3 relative to 1, and so on. In general, a complex value. Note that H_{11} is purely real and equal to 1.

H^I, H^{II} = calibration transfer functions for the microphones in the standard and switched configurations, respectively. See 8.4.

H^c = complex microphone calibration factor accounting for microphone response mismatch.

H_{21}, H_{31}, etc. = transfer function of two microphone signals corrected for microphone response mismatch. In general, a complex value.

NOTE 1—In this context, the term "transfer function" refers to the complex ratio of the Fourier transform of two signals. The term "frequency response function" arises from more general linear system theory (1).[4] This test method shall retain the use of the former term. Users should be aware that modern FFT analyzers might employ the latter terminology.

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[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.
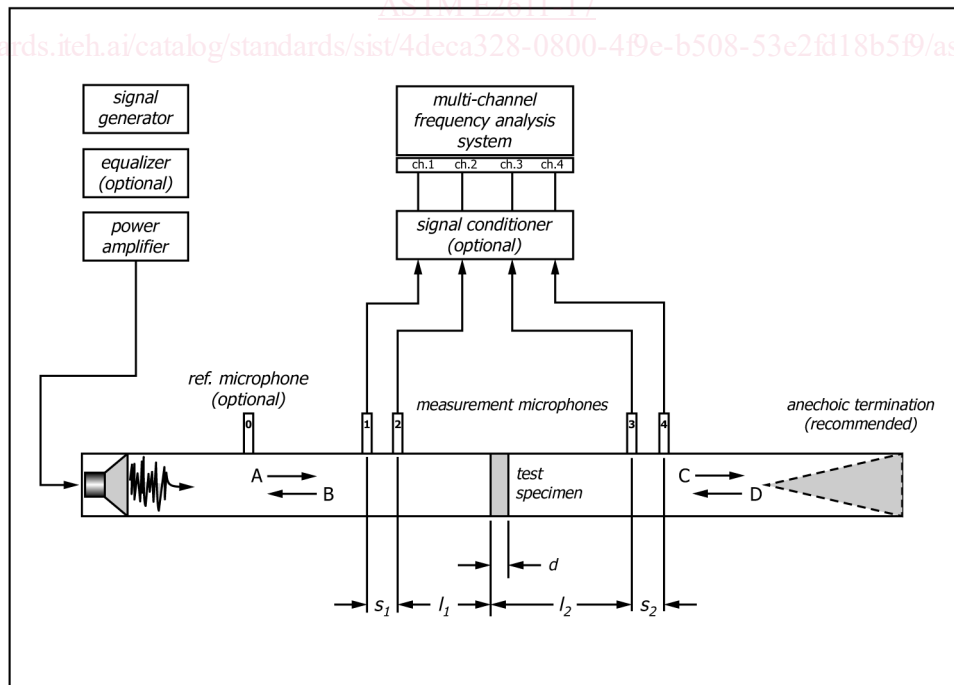
NOTE 1—A, B, C, and D are the forward and backward components of the standing wave field. 1, 2, 3, and 4 are the measurement locations; 0 is an optional reference location. Distances are measured from the specimen reference plane.

FIG. 4~~1~~ Schematic Drawing of ~~the~~ Measurement Setup

$j = \sqrt{-1}$

$k = 2\pi f/c$; wave number in air, m^{-1}.

NOTE 2—In general the wave number is complex where $k' = k^r - jk^i$.k^r is the real component, $2\pi f/c$, and k^i is the imaginary component of the wave number, also referred to as the attenuation constant, nepers/m. This accounts for the effects of viscous and thermal dissipation in the oscillatory, thermoviscous boundary layer that forms on the inner surface of the duct, (**2**). The wave number k' of the propagating wave interior to the material being tested is generally different from that in air, and may be calculated in certain cases from the acoustic transfer matrix.

d = thickness of the specimen in meters; see Fig. 1Fig. 4..

11, 12 = distance in meters from the reference plane (test sample front face) to the center of the nearest microphone on the upstream and downstream side of the specimen; see Fig. 1Fig. 4..

s1, s2 = center-to-center 2 = center-to-center spacing in meters between microphone pairs on the upstream and downstream side of the specimen; see Fig. 1Fig. 4..

R = complex acoustic reflection coefficient.

α = normal incidence sound absorption coefficient.

TL_n = normal incidence transmission loss.

k' = complex wavenumber of propagation in the material, m^{-1}.

Z = characteristic impedance of propagation in the material, rayls.

3.3 *Subscripts, Superscripts, and Other Notation*—The following symbols, which employ the variable X for illustrative purposes, are used in Section 8:

Xc = calibration.

XI,XII = calibration quantities measured with microphones placed in the standard and switched configurations, respectively.

X^- = measured quantity prior to correction for amplitude and phase mismatch.

$|X|$ = magnitude of a complex quantity.

φ = phase of a complex quantity in radians.

Xi = imaginary part of a complex quantity.

Xr = real part of a complex quantity.

3.4 *Summary of Complex Arithmetic*—The quantities in this standard, especially the transfer function spectra, are complex-valued in general. The following may be useful in evaluating the defining equations:

$$e^{j\omega} = \cos(\omega) + j\sin(\omega)$$
$$(A+jB) \times (C+jD) = (AC+BD) + j(AD+BD)$$
$$1/(A+jB) = A/(A^2+B^2) - jB/(A^2+B^2)$$

4. Summary of Test Method

4.1 This test method is similar to Test Method E1050 in that it also uses a tube with a sound source connected to one end and the test sample mounted in the tube. For transmission loss, four microphones, at two locations on each side of the sample, are mounted so the diaphragms are flush with the inside surface of the tube perimeter. Plane waves are generated in the tube using a broadband signal from a noise source. The resulting standing wave pattern is decomposed into forward- and backward-traveling components by measuring sound pressure simultaneously at the four locations and examining their relative amplitude and phase. The acoustic transfer matrix is calculated from the pressure and particle velocity, or equivalently the acoustic impedance, of the traveling waves on either side of the specimen. The transmission loss, as well as several other important acoustic properties of the material, including the normal incidence sound absorption coefficient, is extracted from the transfer matrix.

5. Significance and Use

5.1 There are several purposes of this test:

5.1.1 For transmission loss: *(a)* to characterize the sound insulation characteristics of materials in a less expensive and less time consuming approach than Test Method E90 and ISO 140-3 ("reverberant room methods"), *(b)* to allow small samples tested when larger samples are impossible to construct or to transport, *(c)* to allow a rapid technique that does not require an experienced professional to run.

5.1.2 For transfer matrix: *(a)* to determine additional acoustic properties of the material; *(b)* to allow calculation of acoustic properties of built-up or composite materials by the combination of their individual transfer matrices.

5.2 There are significant differences between this method and that of the more traditional reverberant room method. Specifically, in this approach the sound impinges on the specimen in a perpendicular direction ("normal incidence") only, compared to the random incidence of traditional methods. Additionally, revereration room methods specify certain minimum sizes for test specimens which may not be practical for all materials. At present the correlation, if any, between the two methods is not known. Even though this method may not replicate the reverberant room methods for measuring the transmission loss of materials, it can provide comparison data for small specimens, something that cannot be done in the reverberant room method. Normal incidence

transmission loss may also be useful in certain situations where the material is placed within a small acoustical cavity close to a sound source, for example, a closely-fitted machine enclosure or portable electronic device.

5.3 Transmission loss is not only a property of a material, but is also strongly dependent on boundary conditions inherent in the method and details of the way the material is mounted. This must be considered in the interpretation of the results obtained by this test method.

5.4 The quantities are measured as a function of frequency with a resolution determined by the sampling rate, transform size, and other parameters of a digital frequency analysis system. The usable frequency range depends on the diameter of the tube and the spacing between the microphone positions. An extended frequency range may be obtained by using tubes with various diameters and microphone spacings.

5.5 The application of materials into acoustical system elements will probably not be similar to this test method and therefore results obtained by this method may not correlate with performance in-situ.

6. Apparatus

6.1 The apparatus is a set of two tubes of equal internal area that can be connected to either end of a test sample holder. The number of sets of tubes depends on the frequency range to be tested. A wider frequency range may require multiple measurements on a set of several tubes. At one end of one tube is a loudspeaker sound source. Microphone ports are mounted at two locations along the wall of each tube. A two- or four-channel digital frequency analysis system, or a computer that can effectively do the same calculations, is used for data acquisition and processing.

6.2 *Tube:*

6.2.1 *Construction*—The interior section of the tube may be circular or rectangular and shall have a constant cross-sectional dimension from end-to-end. The tube shall be straight and its inside surface shall be smooth, nonporous, and free of dust, in order to maintain low sound attenuation. The tube construction shall be sufficiently massive so sound transmission through the tube wall is negligible compared with transmission though the sample. See Note 3. Compliant feet or mounts must be used to attenuate extraneous vibration entering the tube structure from the work surface.

NOTE 3—The tube can be constructed from materials including metal, plastic, concrete, or wood. It may be necessary to seal the interior walls with a smooth coating in order to maintain low sound attenuation for plane waves.

6.2.2 *Working Frequency Range*—The working frequency range is:

$$f_l < f < f_u$$

(1)

where:
f = operating frequency, Hz,
f_l = lower working frequency of the tube, Hz, and
f_u = upper working frequency of the tube, Hz.

6.2.3 The lower frequency limit f_l is determined by the spacing of the microphones and the accuracy of the analysis system. The microphone spacing shall be greater than one percent of the wavelength corresponding to the lower frequency of interest.

6.2.4 The upper frequency limit f_u depends on the diameter of the tube, the microphone spacing, and the speed of sound.

6.2.4.1 *Diameter*—In order to maintain plane wave propagation, the upper frequency limit (3) is defined as follows:

$$f_u < \frac{Kc}{d} \quad \text{or} \quad d < \frac{Kc}{f_u}$$

(2)

where:
f_u = upper frequency limit, Hz,
c = speed of sound in the tube, m/s,
d = diameter of the tube, m, and
K = 0.586.

6.2.5 For rectangular tubes, d is defined as the largest section dimension of the tube and K is defined as 0.500. Extreme aspect ratios greater than 2:1 or less than 1:2 should be avoided. A square cross-section is recommended.

6.2.6 Conduct the plane wave measurements within these frequency limits established by Eq 1 in order to avoid cross-modes that occur at higher frequencies, when the acoustical wave length approaches the sectional dimension of the tube.

6.2.7 *Length*—The tube should be sufficiently long for plane waves to be fully developed before reaching the microphones and test specimen. A minimum of three tube diameters must be allowed between sound source and the nearest microphone. The sound source may generate non-plane waves along with desired plane waves. The non-plane waves usually will subside at a distance equivalent to three tube diameters from the source. If measurements are conducted over a wide frequency range, it may be desirable to use a tube, which provides multiple microphone spacing, or to employ separate tubes. The overall tube length also must be chosen to satisfy the requirements of 6.5.3 and 6.5.5.

6.2.8 *Tube Termination*—The termination of the tube is arbitrary in principle, but experience has found that the most useful termination is at least weakly anechoic, causing minimal reflection of the sound wave back down the tube. A convenient way of providing this is to install a wedge or pyramidal shaped section of some sound absorbing material such as glass fiber, about 30 cm long, in the open end of the tube. As the two-load method requires a second measurement with a different tube termination, the wedge should be easily removable so that an open or closed termination may be provided.

6.2.9 *Tube Venting*—Some tube designs cause large temporary pressure variations to be generated during installation or removal of the test specimen. This may induce microphone diaphragm deflection. By including a pressure relief opening of some type, the potential for damage to a microphone diaphragm due to excessive deflection may be reduced. One way to accomplish this is by drilling a small vent, 1 to 2 mm in diameter, through the wall of the tube. It is recommended to locate the tube vent near the sound source, away from microphone locations, and to seal the vent during acoustic measurements.

6.3 *Test Specimen Holder:*

6.3.1 *General Features*—The specimen holder may either be integrated with the tube or may be a separate, detachable extension of the tube.

6.3.2 *Detachable Holder*—As a detachable unit, the holder must make an airtight fit with the end of the tube opposite the sound source. The holder must conform to the interior shape and dimensions of the main part of the tube. The connecting joint must be finished carefully and the use of a sealant, such as petroleum jelly or silicone grease, is recommended.

6.3.3 *Integral Holder*—If the sample holder is in an integral part of the tube, it is recommended to make the installation section of the tube accessible for mounting of the specimen by a removable cover. The mating surfaces must be finished carefully, and the use of a sealant is recommended.

6.3.4 *Circular Holder*—For circular tubes, it is recommended to make the specimen accessible from both the front and back of the sample holder. It is then possible to check the position and flatness of the front and back surface of the specimen. Holders may be constructed from a rigid, clear material, such as acrylic, to facilitate inspection.

6.3.5 *Rectangular Holder*—With rectangular tubes, it is recommended to install the specimen from the side, making it possible to check the fitting and the position of the specimen in the tube and to check the position and flatness of the front surface.

6.4 *Sound Source:*

6.4.1 *Kind and Placement*—The sound source should have a uniform power response over the frequency range of interest. It may either be coaxial with the main tube or joined to the main tube by means of a transition having a straight, tapered, or exponential section (Fig. 12).

6.4.2 *Isolation*—The sound source and transition shall be sealed and isolated from the tube to minimize structure-borne sound excitation of the tube. If a direct radiator loudspeaker is utilized, it shall be contained in a sound-isolating enclosure in order to avoid airborne flanking transmission to the microphones (Fig. 12).

6.4.3 *Termination*—Resonances of the air column in the tube may arise if the mechanical impedance of the loudspeaker membrane or diaphragm is high. In this case, it is recommended to apply a porous absorber coating or lining inside either the tube near the loudspeaker or inside the sound transition. Alternatively, the locations described above may be lightly filled with a low density absorbing material.

6.4.4 *Equalization*—When an absorptive medium is placed near the sound source as described in 6.4.3, significant sound energy will be lost at higher frequencies. An electronic equalizer may then be required to shape the sound spectra measured at the microphone positions so that they are relatively flat. This will minimize the loss of signal-to-noise capability at high frequencies.

6.5 *Microphones:*

6.5.1 *Type, Diameter*—Nominally identical microphones shall be mounted according to 6.5.6. The microphone diameter must be small in comparison with the spacing between microphone ports and also to minimize spatial averaging at higher frequencies across the diaphragm face. It is recommended that the microphone diameter be less than 20 % of the wavelength of the highest frequency of interest. Table 1 provides maximum recommended frequency limits for several typical microphone sizes used at room temperature. Where greater microphone sensitivity is required (e.g., on the transmitted side of high loss samples), larger diameters may be selected for use with large tubes working at low frequencies.

6.5.2 *Microphone Venting*—Some microphones may be designed with a vent to allow for static pressure equalization on either side of the diaphragm. In general, venting may be accomplished either to the inside or to the outside of the tube. Two alternate
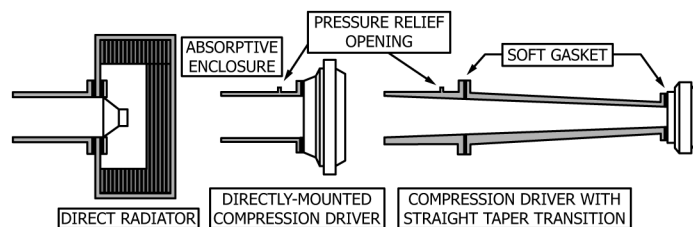

FIG. 12 Sound Source Configuration

TABLE 1 Recommended Frequency Limits for Microphones

Nominal Diameter (in.)	Diaphragm Diameter (mm)	Maximum Frequency (Hz)
1	22.70	3000
½	12.20	5600
¼	5.95	11500

venting methods are available: back-vented (preferred) and side-vented. A microphone pair of either design may be used. Microphones must be sealed carefully when installed in the normal sound transmission tube to avoid leaks, which may interfere with proper operation of the microphone vent, thus causing significant changes to the low frequency response. Blockage of a vent of an individual microphone will alter its phase response, resulting in large errors in the measurements.

6.5.2.1 *Back-Vented Microphones*—Back-vented microphones are vented out through the back of the preamplifier barrel to the outside of the tube. Very low frequency accuracy is improved when the static pressure equalization vent is isolated from the sound field within the sound transmission tube (**4**). Sealing may be accomplished either against the rear of the microphone cartridge barrel or against the protection grid. If the seal is established against the latter, the threads of the protection grid should be sealed with silicone grease to prevent leakage between the tube interior and the back vent (Fig. 23).

6.5.2.2 *Side-Vented Microphones*—The side-venting path proceeds from the vent opening, which is located between the protection grid threads and the diaphragm, to the front of the microphone, and therefore vent to the inside of the tube. Sealing may be established either against the rear of microphone cartridge barrel or against the protection grid. If the seal is established against the latter, the threads of the protection should be sealed with silicone grease to prevent leakage (Fig. 23).

6.5.2.3 *Non-Vented Microphones*—Microphones with non-vented diaphragms may be used if appropriate.

6.5.3 *Spacing*—A large spacing between microphones enhances the accuracy of the measurements, however, the microphone spacing must be less than the shortest half wavelength of interest (**5**).

$$s << \frac{c}{2f_u} \tag{3}$$

where:
s = microphone spacing, m,
c = speed of sound, m/s, and
f_u = upper frequency limit, Hz.

6.5.4 The maximum microphone spacing s must be no larger than 80 % of $c/2f_u$.

6.5.5 *Location*—The minimum distance between the sound source and the closest microphone must follow the requirements of 6.2.7. The minimum distance between the specimen and the closest microphone depends somewhat on the surface characteristics of the specimen. In order to maintain the greatest signal-to-noise ratio, the minimum spacing between the specimen and microphone can be modified as follows.

6.5.5.1 *Flat Surface*—The closest microphone can be moved to within one-half of the tube diameter, or one-half of the largest section dimension in the case of a rectangular tube.

6.5.5.2 *Nonhomogenous Surface*—The closest microphone should be at least one tube diameter, or the largest section dimension in the case of rectangular tube, to help suppress the influence of higher-order modes induced by the rough surface of the specimen.

6.5.5.3 *Asymmetrical Surface*—The closest microphone should be at least two tube diameters (two times the largest section dimension in the case of a rectangular tube) to facilitate the dissipation of higher order modes generated from a rough surface. The higher order modes will decay exponentially as they propagate along the tube.

6.5.6 *Mounting*—Both microphone diaphragms must be flush with the interior surface of the tube using port openings through the side of the tube. If the microphones are switched, care must be taken when the microphones are removed from their port so that the original mounting geometry is maintained when they are replaced. A small stop may be employed to control the depth of each microphone in the port as shown in Fig. 34. The lip should be kept small and identical for both microphone ports.
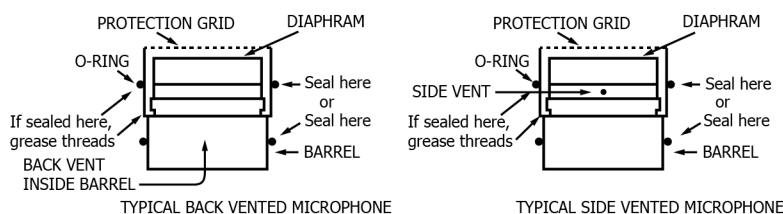

FIG. 23 Microphone Venting and Sealing