Standard Test Method for Measuring Vibration-Damping Properties of Materials[1]

This standard is issued under the fixed designation E756; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 This test method measures the vibration-damping properties of materials: the loss factor, η, and Young's modulus, *E*, or the shear modulus, *G*. Accurate over a frequency range of 50 to 5000 Hz and over the useful temperature range of the material, this method is useful in testing materials that have application in structural vibration, building acoustics, and the control of audible noise. Such materials include metals, enamels, ceramics, rubbers, plastics, reinforced epoxy matrices, and woods that can be formed to cantilever beam test specimen configurations.

1.2 *This standard does not purport to address all 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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E548 Guide for General Criteria Used for Evaluating Laboratory Competence (Withdrawn 2002)[3]

2.2 *ANSI Standard:*

S2.9 Nomenclature for Specifying Damping Properties of Materials[4]

3. Terminology

3.1 *Definitions*—Except for the terms listed below, ANSI S2.9 defines the terms used in this test method.

3.1.1 *free-layer (extensional) damper*—a treatment to control the vibration of a structural by bonding a layer of damping material to the structure's surface so that energy is dissipated through cyclic deformation of the damping material, primarily in tension-compression.

3.1.2 *constrained-layer (shear) damper*—a treatment to control the vibration of a structure by bonding a layer of damping material between the structure's surface and an additional elastic layer (that is, the constraining layer), whose relative stiffness is greater than that of the damping material, so that energy is dissipated through cyclic deformation of the damping material, primarily in shear.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *glassy region of a damping material*—a temperature region where a damping material is characterized by a relatively high modulus and a loss factor that increases from extremely low to moderate as temperature increases (see Fig. 1).

3.2.2 *rubbery region of a damping material*—a temperature region where a damping material is characterized by a relatively low modulus and a loss factor that decreases from moderate to low as temperature increases (see Fig. 1).

3.2.3 *transition region of a damping material*—a temperature region between the glassy region and the rubbery region where a damping material is characterized by the loss factor passing through a maximum and the modulus rapidly decreasing as temperature increases (see Fig. 1).

3.3 *Symbols*—The symbols used in the development of the equations in this method are as follows (other symbols will be introduced and defined more conveniently in the text):

E = Young's modulus of uniform beam, Pa
η = loss factor of uniform beam, dimensionless
E_1 = Young's modulus of damping material, Pa
η_1 = loss factor of damping material, dimensionless
G_1 = shear modulus of damping material, Pa

4. Summary of Method

4.1 The configuration of the cantilever beam test specimen is selected based on the type of damping material to be tested and the damping properties that are desired. Fig. 2 shows four

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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 E33.03 on Sound Transmission.

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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.

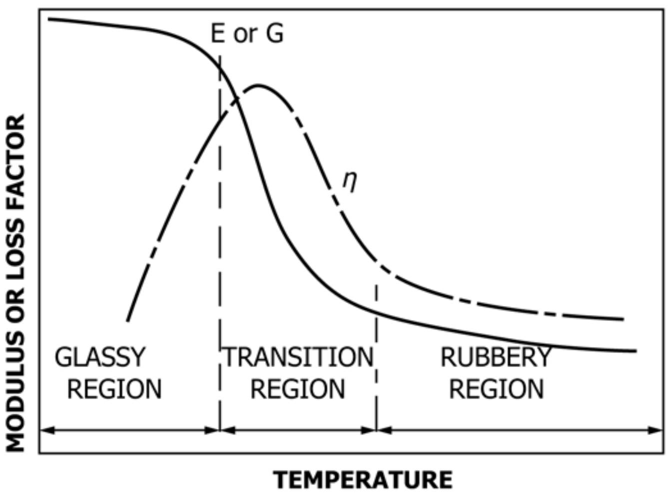

FIG. 1 Variation of Modulus and Material Loss Factor with Temperature (Frequency held constant) (Glassy, Transition, and Rubbery Regions shown)

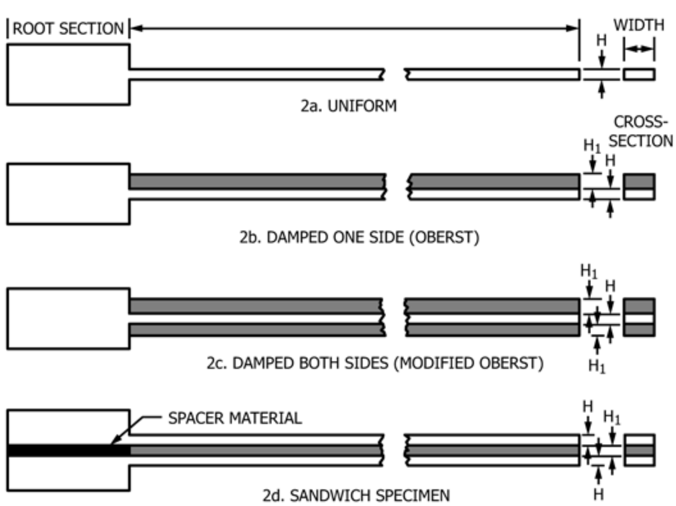

FIG. 2 Test Specimens

different test specimens used to investigate extensional and shear damping properties of materials over a broad range of modulus values.

4.1.1 Self-supporting damping materials are evaluated by forming a single, uniform test beam (Fig. 2a) from the damping material itself.

4.1.2 Non–self-supporting damping materials are evaluated for their extensional damping properties in a two-step process. First, a self-supporting, uniform metal beam, called the base beam or bare beam, must be tested to determine its resonant frequencies over the temperature range of interest. Second, the damping material is applied to the base beam to form a damped composite beam using one of two test specimen configurations (Fig. 2b or Fig. 2c). The damped composite beam is tested to obtain its resonant frequencies, and corresponding composite loss factors over the temperature range of interest. The damping properties of the material are calculated using the stiffness of the base beam, calculated from the results of the base beam tests (see 10.2.1), and the results of the composite beam tests (see 10.2.2 and 10.2.3).

4.1.3 The process to obtain the shear damping properties of non-self-supporting damping materials is similar to the two step process described above but requires two identical base beams to be tested and the composite beam to be formed using the sandwich specimen configuration (Fig. 2d).

4.2 Once the test beam configuration has been selected and the test specimen has been prepared, the test specimen is clamped in a fixture and placed in an environmental chamber. Two transducers are used in the measurement, one to apply an excitation force to cause the test beam to vibrate, and one to measure the response of the test beam to the applied force. By measuring several resonances of the vibrating beam, the effect of frequency on the material's damping properties can be established. By operating the test fixture inside an environmental chamber, the effects of temperature on the material properties are investigated.

4.3 To fully evaluate some non-self-supporting damping materials from the glassy region through the transition region to the rubbery region may require two tests, one using one of the specimen configurations (Fig. 2b or Fig. 2c) and the second using the sandwich specimen configuration (Fig. 2d) (See Appendix X2.6).

5. Significance and Use

5.1 The material loss factor and modulus of damping materials are useful in designing measures to control vibration in structures and the sound that is radiated by those structures, especially at resonance. This test method determines the properties of a damping material by indirect measurement using damped cantilever beam theory. By applying beam theory, the resultant damping material properties are made independent of the geometry of the test specimen used to obtain them. These damping material properties can then be used with mathematical models to design damping systems and predict their performance prior to hardware fabrication. These models include simple beam and plate analogies as well as finite element analysis models.

5.2 This test method has been found to produce good results when used for testing materials consisting of one homogeneous layer. In some damping applications, a damping design may consist of two or more layers with significantly different characteristics. These complicated designs must have their constituent layers tested separately if the predictions of the mathematical models are to have the highest possible accuracy.

5.3 *Assumptions:*

5.3.1 All damping measurements are made in the linear range, that is, the damping materials behave in accordance with linear viscoelastic theory. If the applied force excites the beam beyond the linear region, the data analysis will not be applicable. For linear beam behavior, the peak displacement from rest for a composite beam should be less than the thickness of the base beam (See Appendix X2.3).

5.3.2 The amplitude of the force signal applied to the excitation transducer is maintained constant with frequency. If the force amplitude cannot be kept constant, then the response of the beam must be divided by the force amplitude. The ratio of response to force (referred to as the compliance or receptance) presented as a function of frequency must then be used for evaluating the damping.

5.3.3 Data reduction for both test specimens 2b and 2c (Fig. 2) uses the classical analysis for beams but does not include the effects of the terms involving rotary inertia or shear deformation. The analysis does assume that plane sections remain plane; therefore, care must be taken not to use specimens with a damping material thickness that is much greater (about four times) than that of the metal beam.

5.3.4 The equations presented for computing the properties of damping materials in shear (sandwich specimen 2d - see Fig. 2) do not include the extensional terms for the damping layer. This is an acceptable assumption when the modulus of the damping layer is considerably (about ten times) lower than that of the metal.

5.3.5 The equations for computing the damping properties from sandwich beam tests (specimen 2d–see Fig. 2) were developed and solved using sinusoidal expansion for the mode shapes of vibration. For sandwich composite beams, this approximation is acceptable only at the higher modes, and it has been the practice to ignore the first mode results. For the other specimen configurations (specimens 2a, 2b, and 2c) the first mode results may be used.

5.3.6 Assume the loss factor (η) of the metal beam to be zero.

NOTE 1—This is a well-founded assumption since steel and aluminum materials have loss factors of approximately 0.001 or less, which is significantly lower than those of the composite beams.

5.4 *Precautions:*

5.4.1 With the exception of the uniform test specimen, the beam test technique is based on the measured differences between the damped (composite) and undamped (base) beams. When small differences of large numbers are involved, the equations for calculating the material properties are ill-conditioned and have a high error magnification factor, i.e. small measurement errors result in large errors in the calculated properties. To prevent such conditions from occurring, it is recommended that:

5.4.1.1 For a specimen mounted on one side of a base beam (see 10.2.2 and Fig. 2b), the term $(f_c/f_n)^2(1 + DT)$ should be equal to or greater than 1.01.

5.4.1.2 For a specimen mounted on two sides of a base beam (see 10.2.3 and Fig. 2c), the term $(f_m/f_n)^2(1 + 2DT)$ should be equal to or greater than 1.01.

5.4.1.3 For a sandwich specimen (see 10.2.4 and Fig. 2d), the term $(f_s/f_n)^2(2 + DT)$ should be equal to or greater than 2.01.

5.4.1.4 The above limits are approximate. They depend on the thickness of the damping material relative to the base beam and on the modulus of the base beam. However, when the value of the terms in Sections 5.4.1.1, 5.4.1.2, or 5.4.1.3 are near these limits the results should be evaluated carefully. The ratios in Sections 5.4.1.1, 5.4.1.2, and 5.4.1.3 should be used to judge the likelihood of error.

5.4.2 Test specimens Fig. 2b and Fig. 2c are usually used for stiff materials with Young's modulus greater than 100 MPa, where the properties are measured in the glassy and transition regions of such materials. These materials usually are of the free-layer type of treatment, such as enamels and loaded vinyls. The sandwich beam technique usually is used for soft viscoelastic materials with shear moduli less than 100 MPa. The value of 100 MPa is given as a guide for base beam thicknesses within the range listed in 8.4. The value will be higher for thicker beams and lower for thinner beams. When the 100 MPa guideline has been exceeded for a specific test specimen, the test data may appear to be good, the reduced data may have little scatter and may appear to be self-consistent. Although the composite beam test data are accurate in this modulus range, the calculated material properties are generally wrong. Accurate material property results can only be obtained by using the test specimen configuration that is appropriate for the range of the modulus results.

5.4.3 Applying an effective damping material on a metal beam usually results in a well-damped response and a signal-to-noise ratio that is not very high. Therefore, it is important to select an appropriate thickness of damping material to obtain measurable amounts of damping. Start with a 1:1 thickness ratio of the damping material to the metal beam for test specimens Fig. 2b and Fig. 2c and a 1:10 thickness ratio of the damping material to one of the sandwich beams (Fig. 2d). Conversely, extremely low damping in the system should be avoided because the differences between the damped and undamped system will be small. If the thickness of the damping material cannot easily be changed to obtain the thickness ratios mentioned above, consider changing the thickness of the base beam (see 8.4).

5.4.4 Read and follow all material application directions. When applicable, allow sufficient time for curing of both the damping material and any adhesive used to bond the material to the base beam.

5.4.5 Learn about the characteristics of any adhesive used to bond the damping material to the base beam. The adhesive's stiffness and its application thickness can affect the damping of the composite beam and be a source of error (see 8.3).

5.4.6 Consider known aging limits on both the damping and adhesive materials before preserving samples for aging tests.

6. Apparatus

6.1 The apparatus consists of a rigid test fixture to hold the test specimen, an environmental chamber to control temperature, two vibration transducers, and appropriate instrumentation for generating the excitation signal and measuring the response signal. Typical setups are shown in Figs. 3 and 4.

6.2 *Test Fixture*—The test fixture consists of a massive, rigid structure which provides a clamp for the root end of the beam and mounting support for the transducers.

6.2.1 To check the rigidity and clamping action of the fixture, test a bare steel beam as a uniform specimen (see 8.1.1) using the procedure in Section 9 and calculate the material properties using the equations in 10.2.1. If Young's modulus is not 2.07 E+11 Pa (30 E+6 psi) and the loss factor is not approximately 0.002 to 0.001 for modes 1 and 2 and 0.001 or less for the higher modes, then there is a problem in the fixture or somewhere else in the measurement system (see X2.2).

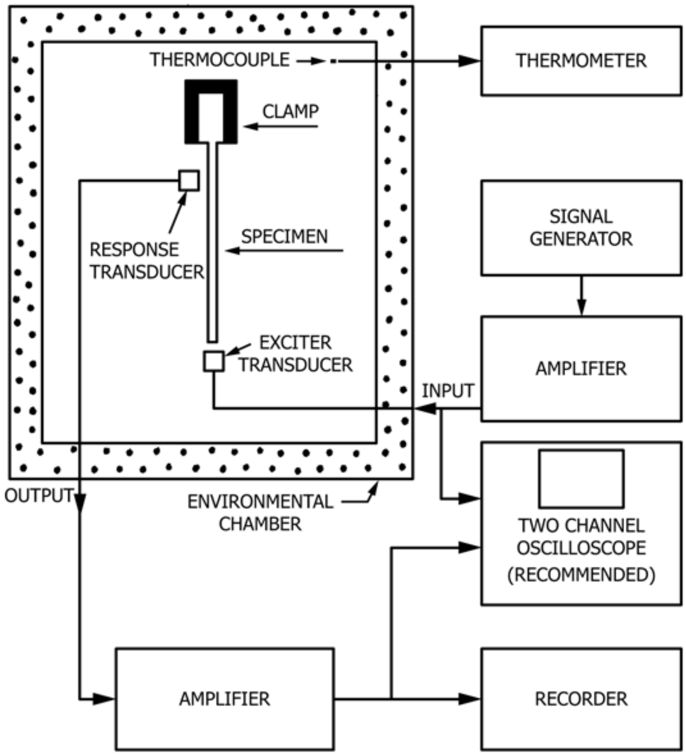

FIG. 3 Block Diagram of Experimental Set-Up Using Separate Excitation and Response Channels and a Sinusoidal Excitation Signal

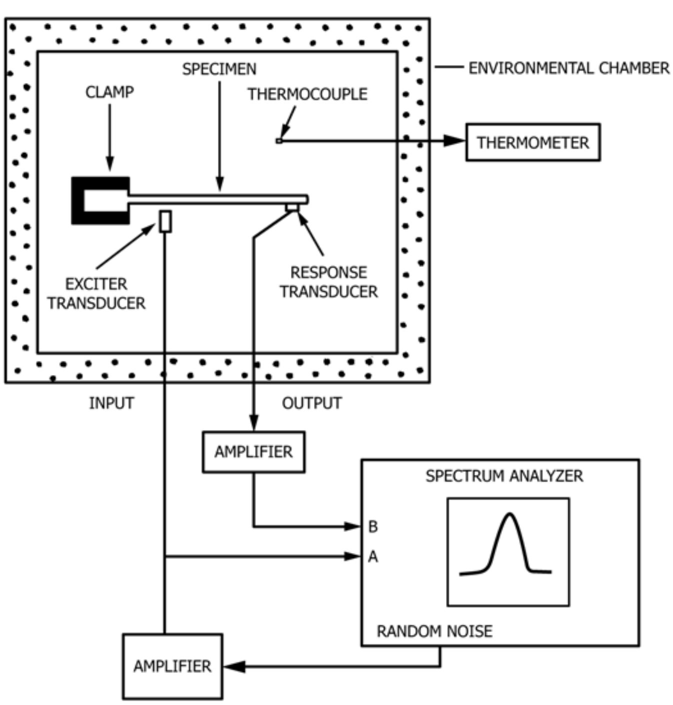

FIG. 4 Block Diagram of Experimental Set-Up Using a Two-Channel Spectrum Analyzer and Random Noise Excitation Signal

6.2.2 It is often useful to provide vibration isolation of the test fixture to reduce the influence of external vibrations which may be a source of measurement coherence problems.

6.2.3 Fig. 3 shows a test fixture with a vertical orientation of the specimen beam. The location of the clamp may be either at the top with the specimen extending downward, as shown in Fig. 3, or at the bottom with the specimen extending upward. Horizontal orientation of the beam is also commonly employed (see Fig. 4).

6.3 *Environmental Chamber*—An environmental chamber is used for controlling the temperature of the test fixture and specimen. As an option, the chamber may also be controlled for other environmental factors such as vacuum or humidity. Environmental chambers often are equipped with a rotating fan for equalizing the temperature throughout the chamber. If it is found that the fan is a source of external vibration in the test beam, the fan may be switched off during data acquisition provided it is conclusively shown that doing so does not affect the test temperature or temperature distribution within the specimen. If the temperature of the chamber and the specimen are not stable, no measurement data may be acquired.

6.4 *Transducers*—Two transducers are utilized. One transducer applies the excitation force, and the other measures the response of the beam. Because it is necessary to minimize all sources of damping except that of the material to be investigated, it is preferable to use transducers of the noncontacting type. Usually the excitation force is applied using an electromagnetic, noncontacting transducer (for example, tachometer pickup) and sometimes response is measured using the same type of transducer. When using stainless steel, aluminum, or nonferrous beams, small bits of magnetic material may be fastened adhesively to the base beam side of the specimen to achieve specimen excitation and measurable response.

6.4.1 At higher frequencies, where noncontacting transducers lack the sensitivity necessary for measurements, subminiature transducers (less than 0.5 g) (that is, accelerometers, strain gages, and so on) may be attached to the beam. Before using a contacting transducer, it must be demonstrated, using the process described in 6.2.1, that the transducer is not a significant source of damping that would contaminate the measurements. The data obtained with these contacting transducers must be identified and a comment cautioning the reader about possible effects (damping and stiffness, especially due to the wiring required by contacting transducers) from this approach must be included in the report.

6.4.2 Fig. 3 shows the arrangement of the transducers with the pick-up transducer near the root and the exciter transducer near the free end. The locations of the transducers may be reversed, as shown in Fig. 4. The locations should be selected to obtain the best signal-to-noise ratio.

6.5 *Instrumentation*—The minimum instrumentation requirements for this test is two channels for vibration data (excitation and response) and one channel for temperature data.

6.5.1 Fig. 3 shows separate excitation and response signal instrumentation channels. Alternatively, a two-channel spectrum analyzer (for example, based on the Fast Fourier Transform algorithm) may be used (see Fig. 4).

6.5.2 The instrumentation may generate either a sinusoidal or random noise excitation signal.

6.5.3 It is recommended that the waveforms in both excitation and response channels be monitored. If separate excitation and response channels are used, as shown in Fig. 3, a two-channel oscilloscope can perform this function. Two-channel spectrum analyzers usually have a similar waveform display function.

7. Sampling

7.1 The damping material test specimen shall be representative of the bulk quantity of material from which the specimen is taken. Where adhesive bonding is employed, care must be taken to minimize lot-to-lot variability of the adhesive's chemical and physical properties.

8. Test Specimen Preparation

8.1 Select the configuration of the test specimen based on the type of damping material to be tested and the damping properties that are desired. The techniques required for preparation of the damping material test specimen often are dependent on the physical characteristics of the material itself. To prepare a damped composite beam may require various techniques such as spray coating, spatula application, or adhesive bonding of a precut sample. Four test specimen configurations are given in Fig. 2 and their use is described as follows:

8.1.1 Test specimen 2a, uniform beam, is used for measuring the damping properties of self-supporting materials. This configuration is also used for testing the metal base beam or beams that form the supporting structure in the other three specimen configurations.

8.1.2 Test specimen 2b, damped one side, is used to evaluate the properties of stiff damping materials when subjected to extensional deformation.

NOTE 2—This is the test specimen configuration that was used by Dr. H. Oberst. (**1**)[5] It is often called the Oberst beam or Oberst bar. The general method of measuring damping using a vibrating cantilever beam is sometimes referred to as the Oberst beam test.

8.1.3 Test specimen 2c, damped two sides, has material coated on both sides of the base beam. The properties are determined under extensional deformation. This configuration allows for simplification in the equations relating to 8.1.2. It also helps to minimize curling of the composite beam during changing temperature conditions due to differences in thermal expansion.

NOTE 3—This test specimen configuration is often called the modified Oberst beam.

8.1.4 Test specimen 2d, sandwich specimen, is used for determining the damping properties of soft materials that will be subjected to shear deformation in their application. A metal spacer of the same thickness as the damping material must be added in the root section between the two base beams of the test specimen (see Fig. 2d). The spacer must be bonded in place with a stiff, structural adhesive system.The dimensions and the resonant frequencies of the two base beams must match. Successful results have been obtained when the free lengths match within ±0.5 mm, the thickness values match within ±0.05 mm. For other beam dimensions that are not used in the data reduction calculations, follow good engineering practice when determining the adequacy of the match. For the resonant frequencies, for each mode used in the calculations, the frequencies must match to within 1.0 % of the lower measured frequency value of the two beams. (See X2.1.2.)

8.2 All test specimens are to have well-defined roots, that is, the end section of the beam to be clamped in the test fixture (see Fig. 2). The root section should have a length of 25 to 40 mm and have a height above the top surface of the beam and a height below the bottom surface of the beam that are each at least equal to the thickness of the composite beam. The presence of these roots is essential for generating useful and meaningful data for most measurements because they give the best simulation of the cantilever boundary condition when the beam is clamped in the rigid test fixture. These roots can be either integrally machined as part of the beam, welded to the beam, or bonded to the beam with a stiff, structural adhesive system (See Appendix X2.1).

8.3 Follow the damping material supplier's recommendations in the selection and application of an adhesive. Lacking such recommendations, the following should be considered: The damping material is usually bonded to the metal beam using a structural grade (versus a contact type) adhesive which should have a modulus much higher (about ten times) than that of the damping material. The thickness of the adhesive layer must be kept to a minimum (less than 0.05 mm), and small in comparison with that of the damping material. If these two rules are not met, deformation may occur in the adhesive layer instead of the damping layer and erroneous data will result. Note that in some cases the damping material is of the self-adhesive type.

8.4 The metal used for the base beam is usually steel or aluminum. Base beam dimensions found to be successful are a width of 10 mm, a free length of 180 to 250 mm, and a thickness of 1 to 3 mm. Other base beam dimensions may be selected based on the desired frequency range of the measurements and the characteristics of the damping material to be tested. The width of the beam is not a factor in the equations for calculating the material properties. However, when selecting the width of the beam, care should be taken to avoid making the beam susceptible to torsional vibrations (see assumptions in 5.3.3).

8.5 The thickness of the damping material may vary, depending on the specific properties of the material and the temperatures and frequencies of interest.

9. Procedure

9.1 Mount the beam in a heavy, rigid fixture providing clamping force around the root of the beam to simulate a fixed end, cantilever boundary condition.

9.2 Place the test fixture, including the beam specimen, inside an environmental chamber.

9.3 Position the transducers on or around the specimen as appropriate for the type of transducer. (Noncontacting type

[5] The boldface numbers in parenthesis refer to the list of references at the end of this test method.

transducers are often placed approximately 1 mm away from the specimen.) Typical setups are shown in Figs. 3 and 4.

9.4 Set the environmental chamber to the desired temperature. Vibration response measurements must be performed at intervals over a wide range of temperatures. Temperature increments of 5°C or 10°C between data acquisition temperatures are common.

9.4.1 The beginning and end points of the temperature range are dependent on the damping material being tested and must be determined by monitoring the loss factor results for the damped composite beam. The range is adequate when the upper and lower slopes, as well as the peak of the loss factor curve, have been well defined by the measurements (see Fig. 1).

9.4.2 To ensure that the test specimen is in full thermal equilibrium during testing, adequate soak time is needed after each new temperature is reached. The specimen-fixture system is considered to be in full thermal equilibrium when the temperature of the entire specimen-fixture system does not differ from the desired test temperature by more than ±0.6 °C. The soak time depends on the thermal mass of the specimen-fixture system. When determining the soak time it is recommended that the minimum soak time not be less than 30 minutes (see Appendix X2.8).

9.5 At each data acquisition temperature, excite the test specimen by applying either a sinusoidal or random signal to the excitation transducer by means of a power amplifier. Measure the response of the beam using the second transducer. When using swept sinusoidal excitation, it is recommended that a manually controlled sweep be used rather than an automatically controlled sweep. This is because a high sweep rate can cause considerable errors in the response spectrum, and a manual sweep allows better control for adapting to the circumstances of the measurement. Fig. 5 shows a typical frequency response spectrum at a fixed temperature.

9.5.1 Measure several resonant modes of the beam for each data acquisition temperature. Figs. 6 and 7 show examples of the variation with temperature in the resonance frequency and loss factor of a damped composite beam. Four or more modes are commonly measured starting with mode 2. Mode 1 is usually not measured (see 5.3.5).

9.5.2 Use the half-power bandwidth method to measure the damping of the composite beam. Using the response curve from each mode, measure the resonant frequency and the frequencies above and below the resonant frequency where the value of the response curve is 3 dB less (the 3 dB down points) than the value at resonance. The frequency difference between the upper 3 dB down point and the lower 3 dB down point is the half-power bandwidth of the mode. The modal loss factor (η) is the ratio of the half-power bandwidth to the resonant frequency (See the loss factor calculation in 10.2.1 for the uniform beam).

9.5.3 Methods other than the half-power bandwidth method may be used for measuring the modal damping of the test specimen provided it can be shown that the other methods give the same results for moderately damped specimens. Examples of other possible methods are modal curve fitting (**2**), Nyquist plots (**3**), dynamic stiffness methods (**4**) or the "n dB" bandwidth method (**5**) (described below).

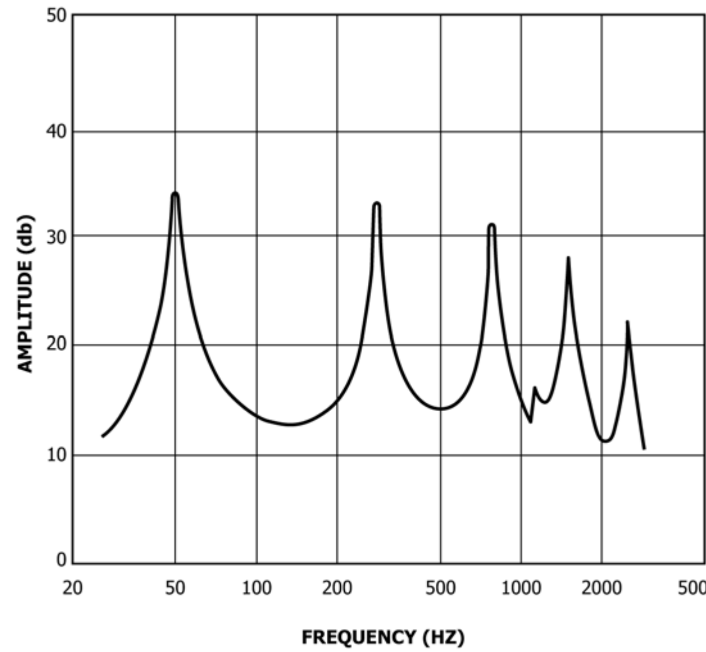

FIG. 5 Typical Frequency Response Spectrum of an Undamped Beam

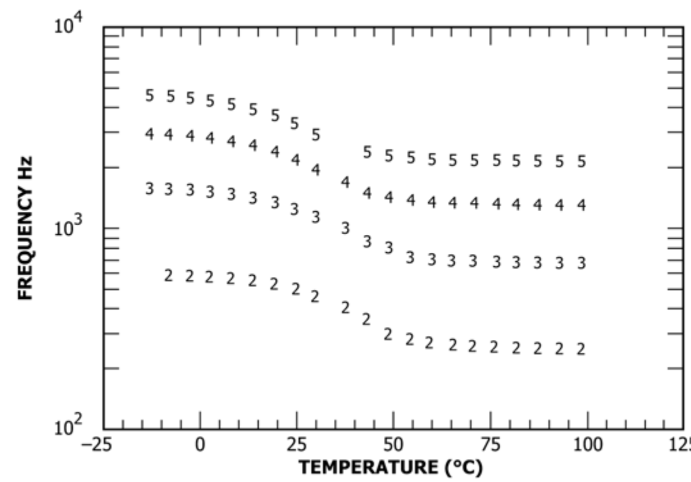

FIG. 6 Variation of Resonance Frequency with Temperature for the Indicated Bending Modes of a Damped Cantilever Beam

9.5.3.1 The "n dB" bandwidth method is similar to the half-power bandwidth method except that the frequencies above and below the resonant frequency are measured where the value of the response curve is n dB less than the value at resonance. The value n is chosen by the user to be a value less than 3 but greater than 0.5 which will allow the width of the resonance to be measured.

9.5.3.2 To compute the modal loss factor using the "n dB" method use the following equation:

$$\eta = \left(\frac{1}{\sqrt{x^2 - 1}} \right) \frac{\Delta f}{f} \tag{1}$$

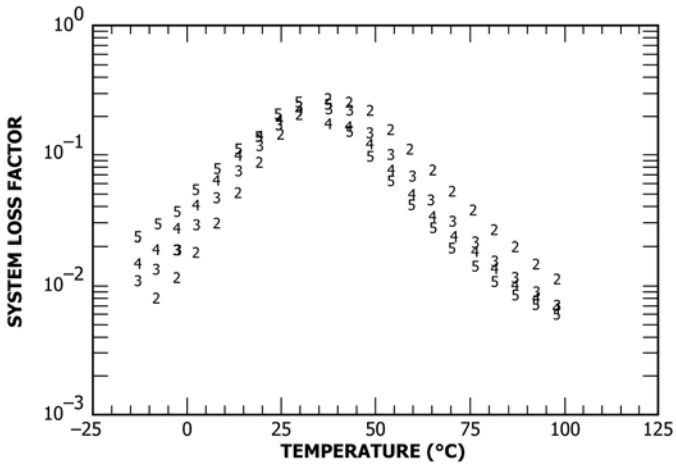

FIG. 7 Variation of Loss Factor with Temperature for the Indicated Bending Modes of a Damped Cantilever Beam

where $x = 10^{(n/20)}$ and n is the "n dB" value chosen by the user.

9.5.4 If a spike appears in the response curve, it may be ignored if it does not affect the half-power bandwidth measurement. If the "n dB" method must be employed to avoid the spike, then report the problem encountered and remedial measures taken.

9.5.5 If a double peak appears in the response curve at the resonance to be measured, the "n dB" method may be employed if the principal peak can be clearly identified. Report the problem encountered and remedial measures taken.

9.5.6 Extra care should be taken when the modal loss factor of the test specimen exceeds 0.20. The following is recommended:

9.5.6.1 Pay close attention to the symmetry (or lack thereof) of the response curve when using the half-power bandwidth or similar methods to determine the loss factor.

9.5.6.2 If the response curve lacks symmetry and specimen preparation techniques cannot be used to enhance the measurability of a damping material (See 5.4.3 regarding the selection of the thickness of the damping material so as to obtain measurable damping values), then select and use an appropriate formula for evaluating the loss factor which reflects the effect of high damping on the shape of the response curve (**6**). The data must be identified in the report and the selected formula must be clearly referenced.

9.5.6.3 Report any problems encountered and remedial measures taken.

10. Calculation

10.1 For all types of test specimens the calculation of the damping material properties requires the resonant frequency of each mode, the half-power bandwidth (3 dB down points) or modal loss factor of each mode, the geometric properties of the beam, and the densities of the materials comprising the specimen.

10.2 Unless the specimen material is self-supporting, the calculation begins with the determination of the frequency response of the uniform (base or bare) beam. The results of the uniform beam calculations serve as input to the calculation of damping material properties. If the specimen material is self-supporting, the calculation ends with the results of the uniform beam.

10.2.1 *Uniform beam (base or bare beam)*—Calculate Young's modulus and the loss factor (see Sections 5.3.6 and 8.1.1) of the beam material from the expressions (**7**):

$$E = \frac{(12\rho l^4 f_n^2)}{(H^2 C_n^2)} \tag{2}$$

and

$$\eta = \frac{(\Delta f_n)}{(f_n)} \tag{3}$$

where:

C_n = coefficient for mode n, of clamped-free (uniform) beam,
E = Young's modulus of beam material, Pa,
f_n = the resonance frequency for mode n, Hz,
Δf_n = the half-power bandwidth of mode n, Hz,
H = thickness of beam in vibration direction, m,
l = length of beam, m,
n = mode number: 1, 2, 3, . . . ,
η = loss factor of beam material, dimensionless,
ρ = density of beam, kg/m^3,

where:

C_1 = 0.55959,
C_2 = 3.5069,
C_3 = 9.8194,
C_4 = 19.242,
C_5 = 31.809, and
C_n = $(\pi/2)(n-0.5)^2$, for n>3.

10.2.2 *Beam Damped One Side (Oberst beam)*—Calculate Young's modulus and the loss factor of the damping material from the expressions (**7**):

$$E_1 = \frac{E}{(2T^3)}\left[(\alpha-\beta)+\sqrt{\{(\alpha-\beta)^2-4T^2(1-\alpha)\}}\right] \tag{4}$$

and

$$\eta_1 = \eta_c\left[\frac{(1+MT)(1+4MT+6MT^2+4MT^3+M^2T^4)}{(MT)(3+6T+4T^2+2MT^3+M^2T^4)}\right] \tag{5}$$

where:

c = index number: 1, 2, 3, . . . ($c=n$),
D = ρ_1/ρ, density ratio,
E = Young's modulus of base beam, Pa,
E_1 = Young's modulus of damping material, Pa,
f_n = resonance frequency for mode n of base beam, Hz,
f_c = resonance frequency for mode c of composite beam, Hz,
Δf_c = half-power bandwidth of mode c of composite beam, Hz,
H = thickness of base beam, m,
H_1 = thickness of damping material, m,
M = E_1/E, Young's modulus ratio,
T = H_1/H, thickness ratio,
α = $(f_c/f_n)^2(1+DT)$,
β = $4+6T+4T^2$,
η_c = $\Delta f_c/f_c$, loss factor of composite beam, dimensionless,
η_1 = loss factor of damping material, dimensionless,

ρ = density of base beam, kg/m^3,
ρ_1 = density of damping material, kg/m^3,

10.2.3 *Beam Damped Both Sides*—Calculate Young's modulus and the loss factor of the damping material from the expressions (7):

$$E_1 = E\frac{[(f_m/f_n)^2(1+2DT)-1]}{(8T^3+12T^2+6T)} \tag{6}$$

and

$$\eta_1 = \eta_m + \left[\frac{E\eta_m}{(E_1\{8T^3+12T^2+6T\})}\right] \tag{7}$$

where:

D = ρ_1/ρ, density ratio,
E = Young's modulus of base beam, Pa,
E_1 = Young's modulus of damping material, Pa,
f_n = resonance frequency for mode n of base beam, Hz,
f_m = resonance frequency for mode m of composite beam, Hz,
Δf_m = half-power bandwidth of mode m of composite beam, Hz,
H = thickness of base beam, m,
H_1 = total thickness of one side of the damping material, m, (Both sides are the same thickness)
m = index number: 1, 2, 3, . . . (m=n),
T = H_1/H, thickness ratio,
η_m = $\Delta f_m/f_m$, loss factor of composite beam, dimensionless,
η_1 = loss factor of damping material, dimensionless,
ρ = density of base beam, kg/m^3,
ρ_1 = density of damping material, kg/m^3,

10.2.4 *Sandwich Specimen*—Calculate the shear modulus and loss factor of the damping material from the expressions (7):

$$G_1 = [A-B-2(A-B)^2-2(A\eta_s)^2]\left[\frac{\left(\frac{2\pi C_n E H H_1}{l^2}\right)}{\{(1-2A+2B)^2+4(A\eta_s)^2\}}\right] \tag{8}$$

and

$$\eta_1 = \frac{(A\eta_s)}{[A-B-2(A-B)^2-2(A\eta_s)^2]} \tag{9}$$

where:

A = $(f_s/f_n)^2(2+DT)(B/2)$,
B = $1/[6(1+T)^2]$,
C_n = coefficient for mode n, of clamped-free (uniform) beam,
D = ρ_1/ρ, density ratio,
E = Young's modulus of base beam, Pa,
f_n = resonance frequency for mode n of Base beam, Hz,
f_s = resonance frequency for mode s of composite beam, Hz,
Δf_s = half-power bandwidth of mode s of composite beam, Hz,
G_1 = shear modulus of damping material, Pa,
H = thickness of base beam, m,
H_1 = thickness of damping material, m,
l = length of beam, m,
s = index number: 1, 2, 3, . . . (s=n),
T = H_1/H, thickness ratio,
η_1 = shear loss factor of damping material, dimensionless,
η_s = $\Delta f_s/f_s$, loss factor of sandwiched specimen, dimensionless,
ρ_1 = density of damping material, kg/m^3,
ρ = density of base beam, kg/m^3,

where:

C_1 = 0.55959,
C_2 = 3.5069,
C_3 = 9.8194,
C_4 = 19.242,
C_5 = 31.809, and
C_n = $(\pi/2)(n-0.5)^2$, for n>3.

10.3 The damping material's modulus (either shear or Young's) and loss factor can be measured with a single beam specimen vibrating in its several modes thus determining the properties as a function of frequency. By conducting the test at several temperatures the properties are determined as a function of temperature. (See also Sections 4.3, 5.4.3, and Appendix X2.6) Typical data showing the effects of frequency and temperature are given in Figs. 8 and 9 for the Young's modulus and material loss factor of a free-layer damping material. In these tests, measurements were made using the base beam damped one side and damped both sides.

11. Report

11.1 The report shall include the following:

11.1.1 A statement, if true in every respect, that the test was by an accredited laboratory (See Annex) and conducted in accordance with this test method. If not true in every respect, the exceptions shall be noted.

11.1.2 The type of test specimen by name; (see Fig. 2) and the basic dimensions of the test specimen and the density of the specimen material that was used in the calculations.

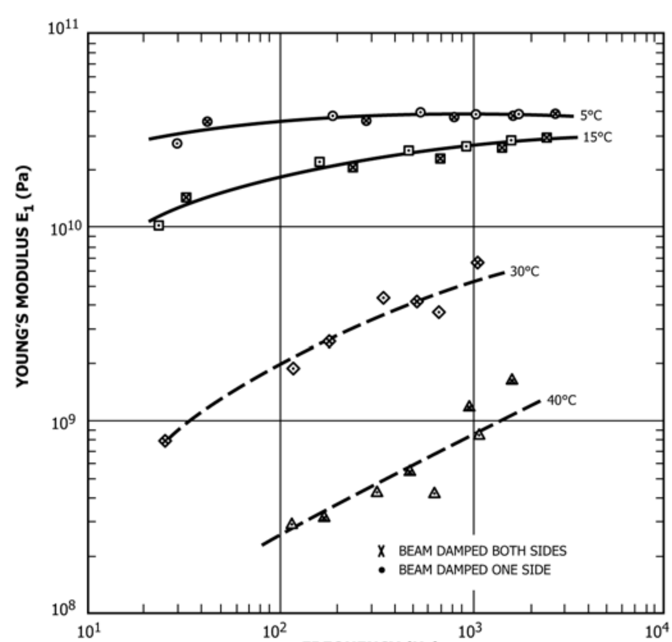

FIG. 8 Young's Modulus Versus Frequency for Various Temperatures

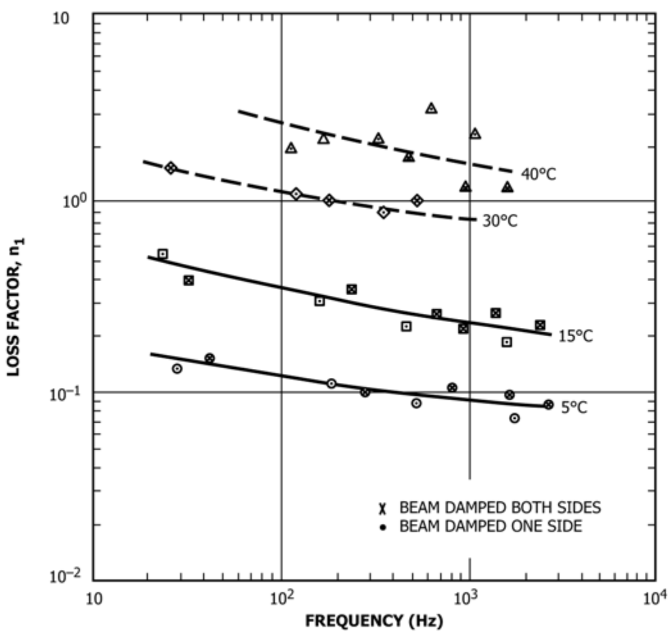

FIG. 9 Damping Material Loss Factor Versus Frequency for Various Temperatures

11.1.3 The identification and type of the particular metal or base material used in the composite test specimen and the density of the base material that was used in the calculations.

11.1.4 The chemical treatment of the metal surface prior to preparation of the damping material (composite) specimen (for example, Electrophoretic Priming Operations (ELPO)).

11.1.5 An identification of the particular adhesive used, where appropriate, along with its thickness.

11.1.6 The frequency, system loss factor, and temperature characteristics of the composite beam for each material tested.

11.1.7 Both test frequencies and temperatures of the base beam(s).

11.1.8 The calculated Young's or shear modulus and the loss factor for each damping material tested.

11.2 Graphic presentation of the data using the Wicket plot (see X2.4) and the Reduced-Frequency Nomogram (see Appendix X3) is recommended.

12. Precision and Bias[6]

12.1 *Precision*—Estimates of precision have been determined from results of an interlaboratory study. For individual temperature-frequency evaluations on extensional damping materials, the coefficient of variation should not exceed 25 % and 20 % for loss factor and modulus respectively. Constrained-layer materials appear to have greater variation in shear modulus; this coefficient of variation should not exceed 45 %.

12.2 *Bias*—There is no known bias; therefore the estimate of accuracy is found in the precision statement.

13. Keywords

13.1 constrained-layer; damping; extensional damping; free-layer; loss factor; shear damping; shear modulus; vibration; vibration damping; Young's modulus

[6] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E33-1001.

ANNEX

(Mandatory Information)

A1. LABORATORY ACCREDITATION

A1.1 Scope

A1.1.1 Laboratory requirements for conducting this test shall conform to all of Guide E548, General Criteria Used for Evaluating Laboratory Competence.

APPENDIXES

(Nonmandatory Information)

X1. RATIONALE FOR USING THE VIBRATING CANTILEVER BEAM TEST METHOD

X1.1 Other Test Methods

X1.1.1 There are numerous methods for evaluating the performance of damping materials. These methods can be roughly divided into two categories, those whose purpose is to rank the performance of damping materials on a defined structure (for example the J1637 test of the Society of Automotive Engineers) and those whose purpose is to measure the properties of the damping material alone so that mathematical models can be used to predict its damping performance when applied to many different types of structures. The latter category contains the method described by this standard as well as a variety of other test methods. Some of these methods include the Dynamic Mechanical Analyzer (DMA)[7,8], the Dynamic Mechanical Thermal Analyzer (DMTA)[9,8], the Viscoanalyzer[10,8], the RSA II[11,8], the Autovibron[12,8], the Model 831[13,8], and so on.

X1.1.2 Each of these test methods, as with all methods, have advantages and disadvantages. Some methods are based on proprietary equipment. Some require material samples with certain physical characteristics. Some methods yield results with fine temperature resolution but only for a single frequency or a narrow range of frequencies. Some methods have difficulty testing materials when the specimen stiffness is very high. It is possible to compare the results from any of these methods by displaying the data using the Reduced-Frequency Nomogram described in Appendix X3. Committee E33 chose to use the vibrating cantilever beam test method after considering the advantages and disadvantages listed below:

X1.2 *Advantages of the Vibrating Cantilever Beam Test Method*:

X1.2.1 The system is reasonably simple to use.

X1.2.2 No proprietary equipment is required.

X1.2.3 Errors can be assessed and kept within limits.

X1.2.4 A single specimen can be used to cover a wide range of frequencies and temperatures. If the selected specimen configuration cannot produce the material properties information in the desired region, alternative configurations are available.

X1.2.5 The damping material is bonded to the specimen beam which often simulates the actual use of the damping material.

X1.2.6 The method lends itself to data acquisition automation.

X1.3 *Disadvantages of the Vibrating Cantilever Beam Test Method*:

X1.3.1 The Vibrating Cantilever Beam test can be conducted only at low strain levels.

[7] The sole source of supply of the apparatus known to the committee at this time is a product of Dupont Instruments, Wilmington, DE 19898.

[8] If you are aware of alternative suppliers, please provide this information to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend.

[9] The sole source of supply of the apparatus known to the committee at this time is a product of Polymer Laboratories, Amherst, MA 01002.

[10] The sole source of supply of the apparatus known to the committee at this time is a product of Metravib Instruments, Cambridge, MA 02138.

[11] The sole source of supply of the apparatus known to the committee at this time is a product of Rheometrics, Piscataway, NJ.

[12] The sole source of supply of the apparatus known to the committee at this time is a product of Imas, Accord, MA.

[13] The sole source of supply of the apparatus known to the committee at this time is a product of MTS Systems Corp., Eden Prairie, MN.

X2. PRACTICAL AIDS FOR TESTING

X2.1 *Preparation of Bare or Base Beams*:

X2.1.1 Each of three methods mentioned in 8.2 for forming the test beam root sections (integrally machined as part of the beam, welded to the beam, or adhesively bonded to the beam) have problems associated with their use. Integrally machining the roots requires expensive machinery and highly skilled operators. Properly welded roots requires skill in welding small parts. Adhesively bonded roots requires a good understanding of the properties of adhesives. Adhesively bonded roots especially must be handled with care because, if the bonded root becomes detached, the bare beam test must be repeated since it is impossible to rebond the root at precisely the same location. Poor adhesive bonds and poor welds especially can cause problems when using the sandwich beam configuration.

X2.1.2 Obtaining matched beams for the Sandwich Specimen Configuration. It generally is very difficult to intentionally construct individual beams whose dimensions and resonant frequencies match. A way to obtain the matched beams needed for the Sandwich Specimen Configuration is to construct and test a batch of base beams with nominally identical dimensions. From experience it has been found that in a batch of 20 to 30 beams there are usually several pairs of beams that meet the criteria described in 8.1.4.

X2.2 *Test Fixture Clamping Force*:

X2.2.1 Poor clamping conditions on the root section of the beam can contribute to the total measured damping of the test specimen, particularly when testing in the glassy region. To minimize this contribution, the following procedure is suggested. Perform several tests on the same specimen, keeping all other conditions the same, while incrementally increasing the clamping force on the beam root section. The appropriate clamping force is attained when successive tests give results within the precision of the measuring system.

X2.3 *Linear Range of Excitation Force*:

X2.3.1 The calculations for the material properties assume that the measurements have been made in the linear range (see 5.3.1). A test for determining the linear range of the measurements is to perform several measurements of the system loss factor on the same composite beam specimen, keeping all other conditions constant, while incrementally increasing the peak displacement. The upper limit of the linear range is identified when successive measurements of the system loss factor differ by more than the precision of the measuring system.

X2.4 *Test for Self-Consistency of Data Using the Wicket Plot*: **(8)**

X2.4.1 The Wicket Plot is a scatter graph of the log material loss factor vs. the log modulus. See Fig. X2.1.

X2.4.2 If the plot is a unique curve, in the shape of an inverted "U," without excessive scatter, then the data are considered self consistent.

X2.4.3 High scatter in the plot, which will make the inverted "U" shape harder to discern, indicates a need to repeat the test after making a change to the test specimen parameters.

X2.4.4 *Caution:* self-consistency of the data does not necessarily imply that the data are accurate.

X2.5 *Multiple Specimen Testing to Improve Confidence*: Confidence in material property results can be improved by testing multiple specimens of a damping material with varying geometries. In temperature-frequency regions where the multiple specimens yield dissimilar results, the material property results should be considered suspect.

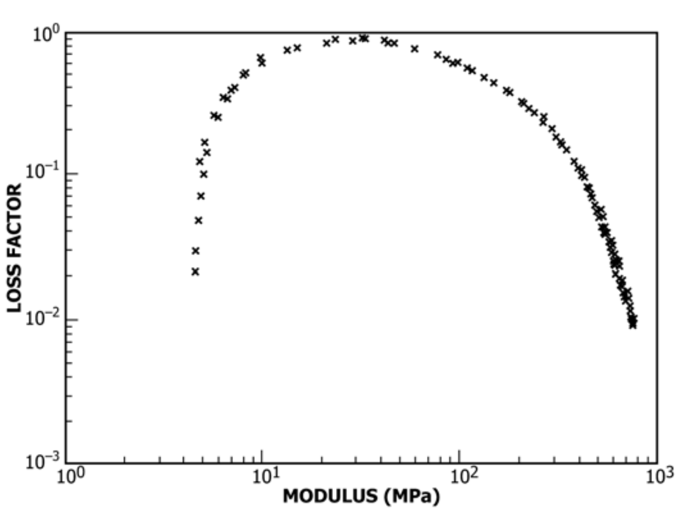

FIG. X2.1 Wicket Plot

X2.6 *Combining Results from Sandwich Specimen Configuration (shear modulus) and Other Configurations (Young's modulus)*:

X2.6.1 To a first approximation, modulus results obtained using the sandwich specimen configuration and one of the other composite beam configurations can be combined by dividing each Young's modulus result by 3 and listing the combined table of results from both configurations as the shear modulus.

X2.7 *Estimating Time of Test*:

X2.7.1 Because the beam test requires that the specimen be in thermal equilibrium when measuring the resonant modes, be sure to allow sufficient time for acquiring all the necessary data. In estimating the time of test, time must be allowed for the chamber to reach the test temperature, a minimum of 30 minutes is required for temperature stabilization, and time is needed for the measurement of the resonant modes. For each temperature in the range of the measurements, it is not uncommon that one hour of test time be required.

X2.8 *Determining the Minimum Soak Time*:

X2.8.1 To determine the minimum soak time it is suggested that a test beam specimen (beam with damping material incorporated) and fixture be instrumented with an array of thermocouples that are spaced along the length of the test beam specimen and at several locations on the fixture. When preparing the test beam specimen, use damping material that is representative of the material type and thickness to be tested. This instrumented test beam specimen and fixture is to be used for acquiring thermal distribution data, not for characterizing a damping material.

X2.8.2 Place the instrumented test beam specimen and fixture in the environmental chamber and set the chamber to a desired test temperature.

X2.8.3 Record the temperature readings from the thermocouple array as a function of time beginning when the chamber temperature has reached the desired temperature within ±0.6°C. The observed soak time for a given test temperature is the time it takes for all the temperature readings of the thermocouple array to reach the desired temperature within ±0.6°C.

X2.8.4 Determine the observed soak times for the temperature range that is possible with the available equipment using temperature increments that will typically be used when characterizing damping materials.

X2.8.5 It is recommend that observed soak times be determined over the temperature range both in an increasing temperature sequence and a decreasing temperature sequence.

X2.8.6 It is recommend that the longest observed soak time be considered the minimum soak time to be used when characterizing damping materials.

X2.8.7 Material factors that can affect the observed soak time include material thickness and thermal conductivity. If, compared to materials that are usually tested, a new material to be tested is much thicker or its thermal conductivity is significantly different, it is likely that the soak time will need to be adjusted. It is recommended that the test be rerun to determine the minimum soak time for any material known to have or suspected of having significantly different thermal characteristics.

X2.8.8 The longest observed soak time typically occurs at the temperature extremes of the environmental chamber's operating range. Because signs of degradation in a chamber's performance often will appear at these extremes, it is suggested that the chamber's long-term performance be monitored by periodically determining the observed soak times at the temperature extremes. Because chambers can often develop slow coolant leaks, it is recommended that attention be paid especially at the cold end of the temperature range.

X3. DATA PRESENTATION USING REDUCED-FREQUENCY NOMOGRAM

X3.1 The Reduced-Frequency Nomogram (RFN) (see Fig. X3.1 and Fig. X3.2) is a data presentation method that allows the lengthy table of loss factor and modulus data obtained at various frequencies and temperatures to be represented as two curves. This permits the extrapolation of data to frequency, or temperature ranges where test data are not available. The basic format uses a multi-cycle, log-log graph with modifications to present the data. A discussion of the basis for using the reduced-frequency nomogram is beyond the scope of this appendix and will not be presented here. The discussion that follows is intended to be a summary of how a reduced-frequency nomogram is generated and how material properties can be read from the nomogram.

X3.2 The left-hand vertical axis is scaled in terms of both the loss factor (η), and the modulus (shear or Young's).

X3.3 The lower horizontal axis is scaled in terms of reduced-frequency (that is, frequency times a shift factor, α_T, which is a function of temperature, T).

X3.3.1 There is no consensus on the best shift factor function, α_T, to use. Several functions have been proposed in the literature (**9**) (for example, WLF, Arrhenius, and so on) and a standard has been published (**10**). Three examples of shift factor equations are listed here. The shift function that is used must be reported when the nomogram is presented. (See X3.3.2 for the definition of the reference temperature, T_0)

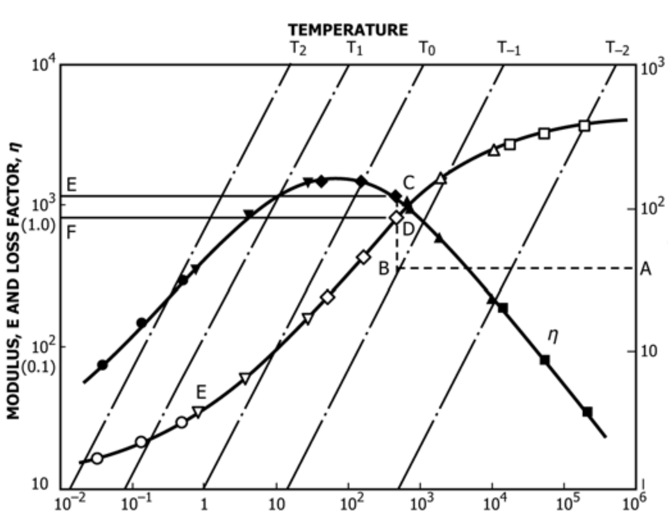

FIG. X3.1 Illustration of the Reduced-Frequency Nomogram

X3.3.1.1 *The WLF equation:*

$$\log\alpha_t = \frac{C_1(T - T_0)}{(C_2 + T - T_0)} \quad \text{(X3.1)}$$

where C_1 and C_2 are constants (for example, C_1 = –12 and C_2=525 or C_1=–9 and C_2 = 315; temperature is in Fahrenheit for both examples) (**9**).

X3.3.1.2 *The Arrhenius equation:*

$$\log\alpha_t = \left(\frac{T_A}{T}\right) - \left(\frac{T_A}{T_0}\right) \quad \text{(X3.2)}$$

where T_A is the "activation temperature" $T_A = Q/(2.303R)$, where Q is the activation energy, and R is the Universal Gas Constant, and the temperature T is in Kelvin.

X3.3.1.3 A quadratic in $1/T$, (referenced in the ISO standard (**10**)) where the temperature T is in Kelvin.

$$\log\alpha_T = a\left(\frac{1}{T} - \frac{1}{T_z}\right) + 2.303\left(\frac{2a}{T_z} - b\right)\log\left(\frac{T}{T_z}\right) + \left(\frac{b}{T_z} - \frac{a}{T_z^2} - S_{AZ}\right)(T - T_z) \quad \text{(X3.3)}$$

Where:

$$a = (D_B C_C - C_B D_C)/D_E$$

$$b = (C_A D_C - D_A C_C)/D_E$$

$C_A = (1/T_L - 1/T_z)^2$	$D_A = (1/T_H - 1/T_z)^2$
$C_B = (1/T_L - 1/T_z)$	$D_B = (1/T_H - 1/T_z)$
$C_C = S_{AL} - S_{AZ}$	$D_C = S_{AH} - S_{AZ}$
	$D_E = D_B C_A - C_B D_A$
$T_Z = 290$	$S_{AZ} = 0.069$
$T_L = 230$	$S_{AL} = 0.2$
$T_H = 360$	$S_{AH} = 0.04$

X3.3.2 The WLF and Arrhenius shift factor equations allow the selection of a reference temperature, T_0. With the WLF equation, proper selection of this temperature permits the data on the nomogram to form reasonably smooth curves with a minimum of scatter. With the Arrhenius equation, the amount of scatter in the data is affected only by the activation of temperature, T_A.

X3.4 Summary of Nomogram Preparation (Using WLF or Arrhenius equations).

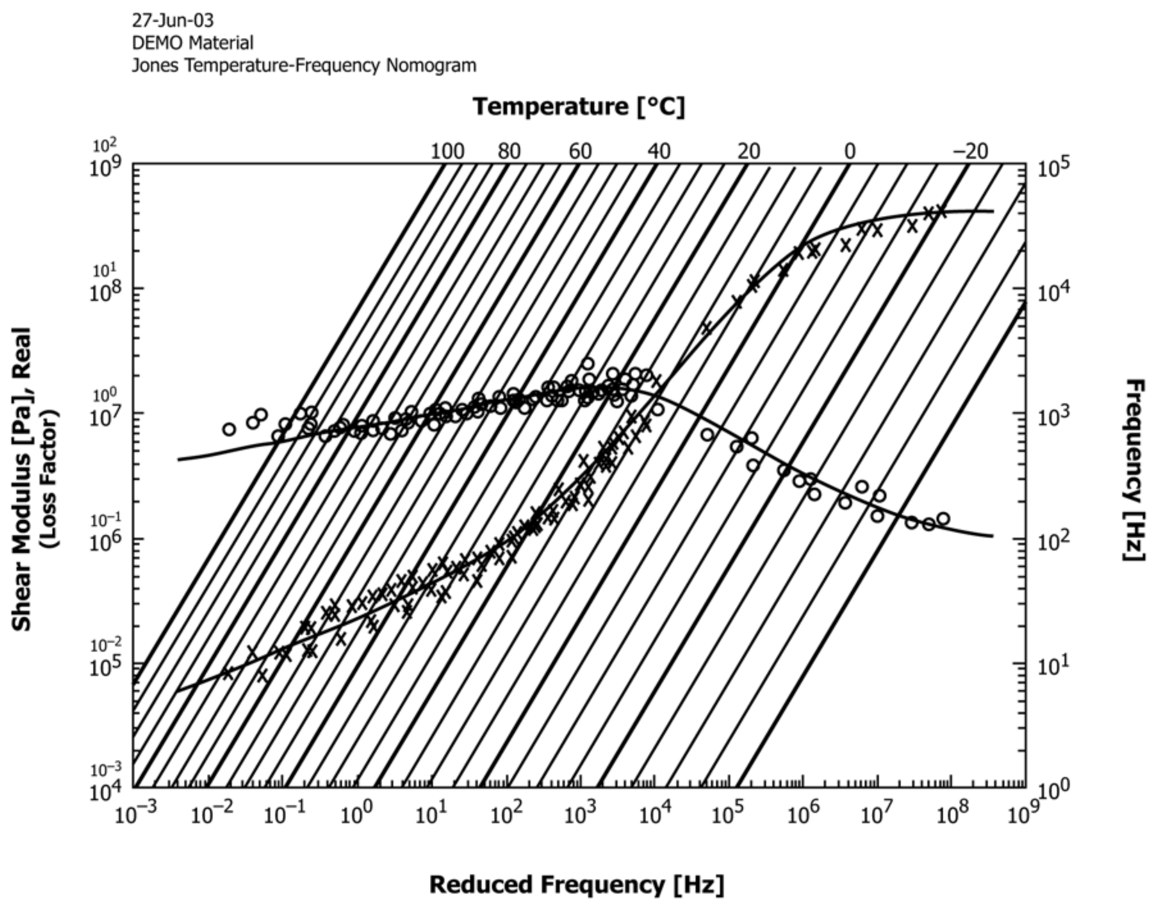

FIG. X3.2 Example of Reduced-Frequency Nomogram Generated Using Actual Data Values.

X3.4.1 To prepare the nomogram, choose an initial T_0. When using the Arrhenius equation also choose an initial T_A.

X3.4.2 Use the shift function to calculate the amount of shift for the data at each temperature, T_i.

X3.4.3 Plot the available loss factor and modulus data versus reduced-frequency.

X3.4.4 Visually judge the degree of matching for both the loss factor and modulus curves with the chosen degree of shift.

X3.4.4.1 When T_0 (T_A when using the Arrhenius equation) is properly chosen, the valid material properties data should produce two curves similar to those shown in Fig. X3.1.

X3.4.4.2 If T_0 (T_A when using the Arrhenius equation) is improperly chosen, the matching will not be satisfactory: the curves may not be smooth; the scatter may be too great. Choose a new value of T_0 (T_A when using the Arrhenius equation) and repeat the process from X3.4.2.

X3.4.5 Once the proper T_0 (T_A when using the Arrhenius equation) has been found, the shift factor information can be added to the nomogram to make it easier to read the data.

X3.4.5.1 Start by relabeling the right-hand vertical scale for frequency.

X3.4.5.2 Along the frequency line f = 1, mark the points at desired temperatures (for example, T_{-2}, T_{-1}, T_0, T_1, T_2, . . .) as identified by $f\alpha_T = (1)\alpha_T$.

X3.4.5.3 Along the frequency line f = 10, mark the points at desired temperatures (for example, T_{-2}, T_{-1}, T_0, T_1, T_2, . . .) as identified by $f\alpha_T = (10)\alpha_T$.

X3.4.5.4 Similarly, the process can be repeated for frequency lines equal to 100, 1000, and so on. The set of points corresponding to each desired temperature yields a diagonal line which can be labeled with the appropriate temperature where it intersects the upper horizontal axis of the nomogram as shown in Fig. X3.1.

X3.4.5.5 Once the nomogram has been completed, it is possible to curve fit the loss factor and modulus data in the nomogram format. The equations from the curve fit make it very convenient for damping design modeling and predictions using a computer.

X3.4.5.6 When presenting a completed Reduced-Frequency Nomogram the following information is required: the name of the damping material, its density, the shift factor equation, and the value selected for T_0.

X3.5 *Reading Damping Material Properties from the Nomogram*:

X3.5.1 Determine the frequency and temperature for which the damping material properties are desired.

X3.5.2 Locate the frequency of interest on the right-hand axis (for example, point A in Fig. X3.1).

X3.5.3 Draw a horizontal line across the nomogram from the frequency point until it intersects the diagonal line of the temperature of interest (for example, point B in Fig. X3.1).

X3.5.4 From the point of intersection draw a vertical line until it intersects the loss factor curve and the modulus curve (for example, points C and D respectively in Fig. X3.1).

X3.5.5 From the point of intersection on the loss factor curve (for example, point C in Fig. X3.1), draw a horizontal line to the left until it intersects the left-hand vertical axis (for example, point E in Fig. X3.1). Read the loss factor value using the appropriate scale.

X3.5.6 From the point of intersection on the modulus curve (for example, point D in Fig. X3.1) .draw a horizontal line to the left until it intersects the left-hand vertical axis (for example, point F in Fig. X3.1). Read the modulus value using the appropriate scale.

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