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Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials —

Part 2: Resonance method

Vibrations et chocs mécaniques — Caractérisation des propriétés mécaniques dynamiques des matériaux visco-élastiques —

Partie 2: Méthode de résonance

Reference number
ISO 18437-2:2005(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 18437-2 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*.

ISO 18437 consists of the following parts, under the general title *Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials*:

— *Part 2: Resonance method*

— *Part 3: Cantilever shear beam method*

Part 4 (*Impedance method*) is under preparation.

Introduction

Visco-elastic materials are used extensively to reduce vibration magnitudes in structural systems through the dissipation of energy (damping) or isolation of components, and in acoustical applications that require a modification of the reflection, transmission or absorption of energy. Such systems often require specific dynamic mechanical properties in order to function in an optimum manner. Energy dissipation is due to interactions on the molecular scale and is measured in terms of the lag between stress and strain in the material. The visco-elastic properties (modulus and loss factor) of most materials depend on frequency, temperature, and strain magnitude. The choice of a specific material for a given application determines the system performance. The goal of this part of ISO 18437 is to provide details in constructing the resonance apparatus, in setting up the measurement equipment, in performing the measurements and analysing the resultant data. A further intent is to assist users of this method and to provide uniformity in the use of this method. This part of ISO 18437 applies to the linear behaviour observed at small strain magnitudes.

Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials —

Part 2:
Resonance method

1 Scope

This part of ISO 18437 defines a resonance method for determining from laboratory measurements the dynamic mechanical properties of the resilient materials used in vibration isolators. It is applicable to shock and vibration systems operating from a fraction of a hertz to about 20 kHz.

This part of ISO 18437 is applicable to resilient materials that are used in vibration isolators in order to reduce

a) transmissions of unwanted vibrations from machines, structures or vehicles that radiate sound (fluid-borne, airborne, structure-borne, or others), and

b) the transmission of low-frequency vibrations that act upon humans or cause damage to structures or sensitive equipment when the vibration is too severe.

The data obtained with the measurement methods that are outlined in this part of ISO 18437 and further detailed in ISO 18437-3 are used for

- the design of efficient vibration isolators,
- the selection of an optimum material for a given design,
- the theoretical computation of the transfer of vibrations through isolators,
- information during product development,
- product information provided by manufacturers and suppliers, and
- quality control.

The condition for the validity of the measurement method is linearity of the vibrational behaviour of the isolator. This includes elastic elements with nonlinear static load deflection characteristics, provided that the elements show approximate linearity in their vibrational behaviour for a given static preload.

Measurements using this method are made over one or two decades in frequency at a number of temperatures. By applying the time-temperature superposition principle, the measured data are shifted to generate dynamic mechanical properties over a much wider range of frequencies (typically 10^{-3} to 10^{9} Hz at a single reference temperature) than initially measured at a given temperature.

NOTE For the purposes of this part of ISO 18437, the term “dynamic mechanical properties” refers to the determination of the fundamental elastic properties, e.g. the complex Young's modulus as a function of temperature and frequency and, if applicable, a static preload.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 472:1999, *Plastics — Vocabulary*

ISO 2041:1990, *Vibration and shock — Vocabulary*

ISO 4664-1:2005, *Rubber, vulcanized or thermoplastic — Determination of dynamic properties — Part 1: General guidance*

ISO 6721-1:2001, *Plastics — Determination of dynamic mechanical properties — Part 1: General principles*

ISO 10112:1991, *Damping materials — Graphical presentation of the complex modulus*

ISO 10846-1:1997, *Acoustics and vibration — Laboratory measurement of vibro-acoustic transfer properties of resilient elements — Part 1: Principles and guidelines*

ISO 23529:2004, *Rubber — General procedures for preparing and conditioning test pieces for physical test methods*

3 Terms and definitions

For the purposes of this document, the following terms and definitions given in ISO 472, ISO 2041, ISO 4664-1, ISO 6721-1, ISO 10112, ISO 10846-1, ISO 23259 and the following apply.

3.1
Young's modulus
E^*
quotient of normal stress (tensile or compressive) to resulting normal strain, or fractional change in length

NOTE 1 Unit is the pascal (Pa).

NOTE 2 Young's modulus for visco-elastic materials is a complex quantity, having a real part E' and an imaginary part E''.

NOTE 3 Physically, the real component of Young's modulus represents elastic-stored mechanical energy. The imaginary component is a measure of mechanical energy loss. See 3.2.

3.2
loss factor
ratio of the imaginary part of the Young's modulus of a material to the real part of the Young's modulus (the tangent of the argument of the complex Young's modulus)

NOTE When there is energy loss in a material, the strain lags the stress by a phase angle, δ. The loss factor is equal to tan δ.

3.3
time-temperature superposition
principle by which, for visco-elastic materials, time and temperature are equivalent to the extent that data at one temperature are superposed upon data taken at a different temperature merely by shifting the data curves along the frequency axis

3.4
shift factor
measure of the amount of shift along the logarithmic (base 10) axis of frequency for one set of constant-temperature data to superimpose upon another set of data

3.5
glass transition temperature

T_g

temperature at which a visco-elastic material changes state from glassy to rubbery, and corresponds to a change in slope in a plot of specific volume against temperature

NOTE 1 Unit is degrees Celsius (°C).

NOTE 2 The glass transition temperature is typically determined from the inflection point of a specific heat vs. temperature plot and represents an intrinsic material property.

NOTE 3 T_g is not the peak in the dynamic mechanical loss factor. That peak occurs at a higher temperature than T_g and varies with the measurement frequency; hence is not an intrinsic material property.

3.6
resilient material

visco-elastic material intended to reduce the transmission of vibration, shock or noise

NOTE 1 It is sometimes referred to as an elastic support, vibration isolator, shock mounting, absorber or decoupler.

NOTE 2 The reduction may be accomplished by the material working in tension, compression, torsion, shear, or a combination of these.

3.7
linearity

property of the dynamic behaviour of a resilient material if it satisfies the principle of superposition

NOTE 1 The principle of superposition is stated as follows: if an input $x_1(t)$ produces an output $y_1(t)$ and in a separate test an input $x_2(t)$ produces an output $y_2(t)$, superposition holds if the input $\alpha x_1(t) + \beta x_2(t)$ produces the output $\alpha y_1(t) + \beta y_2(t)$. This holds for all values of α, β and $x_1(t)$, $x_2(t)$, where α and β are arbitrary constants.

NOTE 2 In practice, the above test for linearity is impractical. Measuring the dynamic modulus for a range of input levels can provide a limited check of linearity. For a specific preload, if the dynamic transfer modulus is nominally invariant, the system measurement is considered linear. In effect this procedure checks for a proportional relationship between the response and the excitation.

4 Test equipment (see Figure 1)

4.1 Electro-dynamic vibration generator

An electro-dynamic vibration generator is required to provide a driving force for the test specimen, producing an oscillating displacement in the vertical direction. The dynamic strain level shall be adjusted to assure linear behaviour (see Annex A). The following specifications are typical:

- frequency range: 25 Hz to 10 kHz;
- force rating: > 5 N;
- peak displacement: $< 0{,}1$ mm.

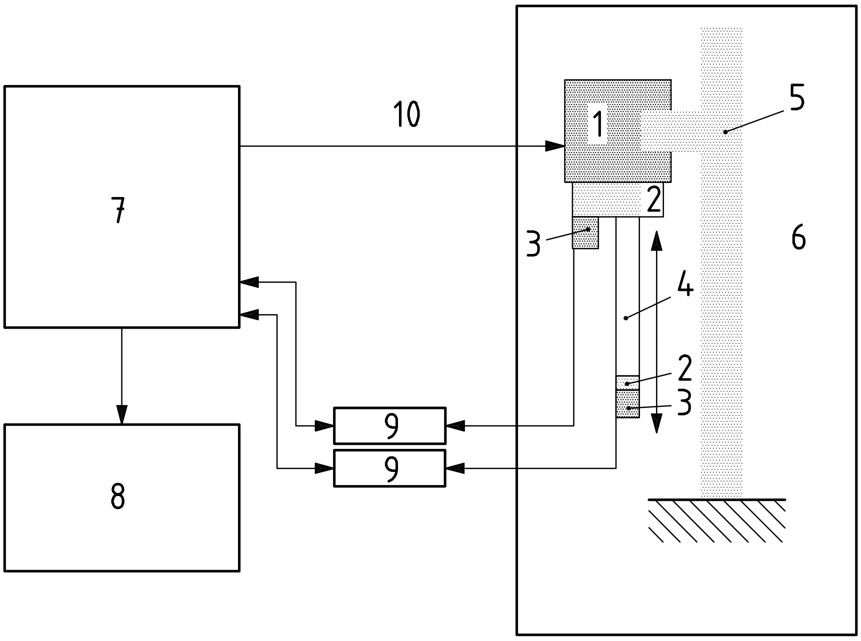
4.2 Accelerometers

A matched pair of accelerometers is required, or a relative calibration correction shall be applied. Piezoelectric accelerometers, with the following specifications, are typical of those required to measure the input and output acceleration of the test sample:

- frequency range: 25 Hz to 10 kHz;
- charge sensitivity: > 1 pC/g.

The mass of the accelerometer plus the lower mounting block should be as small as possible (see 5.1).

NOTE It is possible to use other types of sensors, but they need to be functionally equivalent.



Key

1	electro-dynamic vibration generator
2	mounting blocks
3	accelerometers
4	test specimen
5	test stand
6	environmental chamber
7	dual-spectrum analyser
8	computer
9	charge amplifiers
10	noise source

Figure 1 — Schematic diagram of the resonance apparatus

4.3 Charge amplifiers

Charge amplifiers with a sensitivity of not less than 1 mV/pC are required to amplify the output signal from the accelerometers. Alternatively, piezoelectric accelerometers with built-in amplifiers may be used.

4.4 Test stand

A test stand is needed to suspend the vibration generator and the test sample in a vertical position, as shown in Figure 1. The sample and vibration generator shall be positioned so as to eliminate or minimize any horizontal motion.

NOTE The presence of horizontal motion will appear as spurious peaks in the spectra.

4.5 Environmental chamber

An environmental chamber is required to cool the test sample to a temperature below room temperature. This temperature shall be maintained until the sample has reached equilibrium, then the temperature of the sample shall be increased in increments of 5 °C. The chamber should be capable of operating over the temperature range from 60 °C to 70 °C and should be controllable to within 0,5 °C. The temperature sensor shall be appropriately calibrated.

NOTE 1 The required temperature range is appropriate for a visco-elastic material having a glass transition temperature greater than −45 °C. Materials with lower glass transition temperatures will require a lower starting temperature point.

NOTE 2 Some materials are sensitive to humidity and it may be desirable to control or at least record the relative humidity in the chamber.

4.6 Dual-channel spectrum analyser

A dual-channel spectrum analyser with the following capabilities is typical of that required to drive the vibration generator and analyse the accelerometer output signals:

- random noise source;
- two input channels;
- frequency response function (FFT), and coherence analysis;
- r.m.s. signal averaging;
- frequency range: 25 Hz to 10 kHz;
- dynamic range: $>$ 42 dB;
- band selectable zoom FFT resolution: 0,1 Hz.

4.7 Computer

The use of a computer is advantageous to automate the calibration, data acquisition and processing.

5 Operating procedures

5.1 Sample preparation and mounting

Mould test specimens into the shape of a bar. The mould should be at least 150 mm long, with uniform square lateral dimensions of $\left(6{,}0_{-0{,}1}^{0}\right)$ mm. Trim the moulded specimen of all flash and cut to a length of 100 mm ± 10 mm, using a razor blade. Square the ends of the bar by machining if necessary. The bar shall be able to stand upright on either end without support. Square ends are required to obtain a good bond between the test specimen and mounting blocks.

A uniform circular cross-section of about 6 mm to 8 mm diameter is also acceptable instead of a square bar.

Lengths not less than one-half the 100 mm specified or not more than twice that length are also acceptable.

NOTE 1 Shorter lengths produce resonances at higher frequencies and lead to fewer peaks being observed due to higher absorption at higher frequencies. Longer lengths produce resonances at lower frequencies and lead to problems due to bending of the longer specimen.

Three properties of the specimen that are required in the analyses shall be measured before bonding the specimen to the mounting blocks. In accordance with ISO 23529, determine the length, in metres, to four significant digits. Determine, using a balance, the mass of the specimen, in kilograms, to four significant digits. Determine the density of the specimen in kg/m^3 by a water-displacement technique.

NOTE 2 A method such as ASTM D 792[1] is acceptable.

At the vibration generator end (Figure 1) of the specimen, bond the specimen and one accelerometer by adhesive to the mounting block. The dimensions of the mounting steel block are typically 25 mm × 20 mm × 10 mm. Both rigid epoxy and cyanoacrylate adhesives are acceptable.

The adhesive thickness shall be less than 0,5 mm and the modulus of the adhesive shall be greater than that of the material to be measured. Under these conditions, it has been shown that the adhesive does not affect the measurement[2].

Bond the second accelerometer to the accelerometer mounting block (Figure 1), which is then bonded to the specimen. Use the same adhesive for bonding as used previously. The accelerometer mounting block shall have the same cross-section as the sample (steel cube, 6 mm on each side, or appropriate diameter if a circular specimen is used). Determine, using a balance, the mass of the accelerometer and mounting block, in kilograms, to three significant digits.

NOTE 3 The purpose of the accelerometer mounting block is to avoid the wear and tear of repeatedly bonding and de-bonding the accelerometer to the specimen. In the arrangement specified, the accelerometer is bonded to one side of the mounting block and remains there. The other end of the block is de-bonded and re-bonded each time a new specimen is mounted.

A small accelerometer mounting block is desirable to minimize creep in the sample. While the block should be the same cross-sectional area as the sample, it is acceptable for the block to be shorter than the sample, but not longer.

5.2 Conditioning

5.2.1 Storage

The time delay between moulding or vulcanization and testing and preconditioning of samples shall be in accordance with ISO 23529.

5.2.2 Temperature

Test pieces shall be thermally conditioned before each sequence of tests. At each test temperature, it is essential that the test piece be conditioned for sufficient time to reach equilibrium, but conditioning shall be no longer than necessary, particularly at higher temperatures, to avoid ageing effects. The conditioning time will depend on the test piece dimensions and the temperature. Guidance is given in ISO 23529.

5.2.3 Mechanical conditioning

Mechanical conditioning is generally omitted since only a single, very small strain is used as in free vibration applications. For large strains, the dynamic visco-elastic properties of many resilient materials are very dependent on the strain magnitude and temperature history. For such materials, it is recommended that the test pieces be preconditioned to obtain consistent and reproducible results. The test pieces shall be mechanically conditioned before testing to remove irreversible “structure”. The conditioning shall consist of at least six cycles at the maximum strain and temperature to be used in the series of tests. A minimum of 12 h rest period is required between mechanical conditioning and testing to allow reversible “structure” to equilibrate.

5.2.4 Humidity conditioning

Humidity is known to affect the physical properties of many resilient materials, especially urethanes. To ensure that measurements are made under reproducible conditions, samples shall be stored in a controlled humidity environment for one week before testing. The controlled humidity is achieved by keeping the sample in a closed container that maintains a relative humidity of 50 % to 55 %. The temperature in the container shall be controlled between 20 °C and 25 °C during the conditioning period. Guidance is given in ISO 483.

5.3 Number of test pieces

In order to obtain an indication of the variability of the material, it is recommended that a minimum of three representative samples be tested.

5.4 Data acquisition

5.4.1 The following functions are performed in the data acquisition process.

a) The vibration generator is driven by the spectrum analyser with a random noise source.

b) Fourier transform analyses of the electrical signals from the two accelerometers are performed by the two-channel spectrum analyser.

c) The frequency response function of the test sample and the coherence of the measurement are calculated from the Fourier transform analyses of the output and input signals. The averaging process used in the calculations is repeated 32 times to improve the coherence. Coherence shall be greater than 0,95.

d) The test is completed when the analyser has displayed the magnitude and phase of the frequency response function over its frequency range.

The data shall be displayed so as to observe that, at certain frequencies, the magnitude of the frequency response function, known as the acceleration ratio, A, has resonance peaks in the kilohertz region, while the phase angle, ϕ, goes through several cycles of 360°. A typical plot of acceleration ratio and phase angle as a function of frequency is shown in Figure 2. The acceleration ratio and frequency are measured at multiple values of the phase angle:

$$\phi = -90(2n - 1) \tag{1}$$

where n is the resonance mode number.

NOTE 1 It is important to keep in mind that the resonance frequency is not the frequency of the peak in the acceleration ratio but the frequency at which the phase angle is an odd multiple of 90° as in Equation (1). The peak in the acceleration ratio occurs at a lower frequency depending on the loss factor.

NOTE 2 Extraneous modes occur as a result of improper sample mounting or vibration generator misalignment. These modes result from a component of the excitation that is perpendicular to the desired uni-axial excitation. These modes are easily identified as they are interlaced with the desired modes and produce inconsistent dynamic moduli. While such modes could be simply ignored, it is better to take steps to correct the problem by properly aligning the sample so that it undergoes only uni-axial excitation.

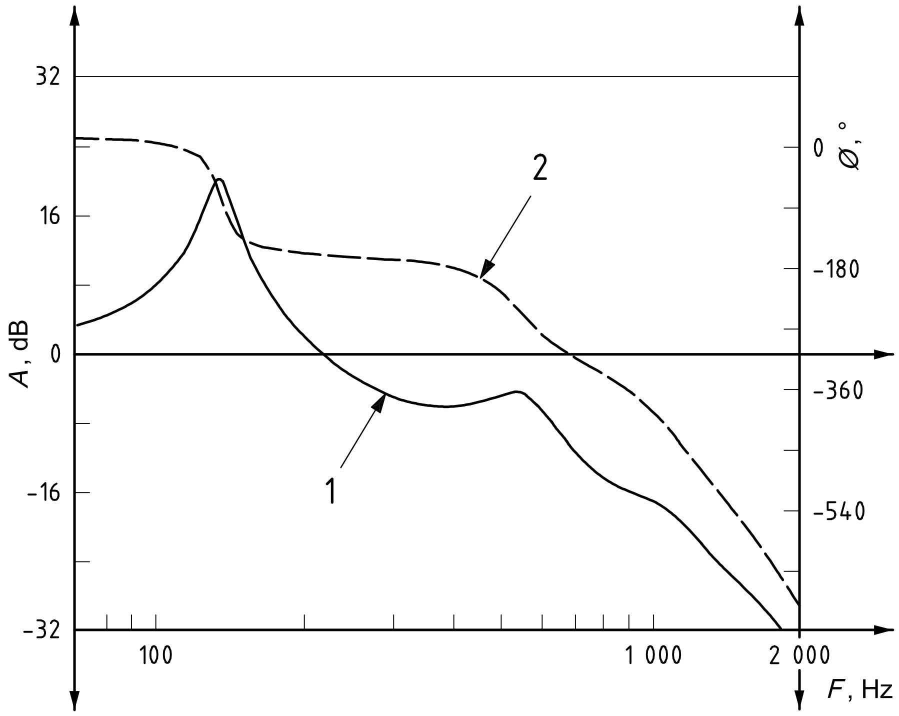
5.4.2 The number of resonance peaks that are measured depends on the modulus and loss factor of the material but, typically, there are three to six peaks. As shown in Figure 2, the phase decreases with frequency, which implies that the acceleration at the free end lags behind that at the driven end.

The values required for each resonance mode of the test specimen are the resonance frequency and acceleration ratio. They are determined as follows.

a) Estimate values of the resonance frequencies using the spectrum analyser set to operate over the complete frequency range from 25 Hz to 18 kHz. Determine the phase angle to within 5° during this step.

b) For each resonance frequency in turn, set the estimated value of the resonance frequency as the centred frequency with the spectrum analyser set for a frequency range that allows a finer resolution, typically about 1 Hz. It may be necessary to use an intermediate frequency range before going to the highest resolution if the estimated evaluation of the resonance frequency was not sufficiently accurate.

c) Determine the final values for the phase angle to within 0,5°, the resonance frequency to within 0,1 Hz, and the acceleration ratio to within 0,1 dB.



Key

1	acceleration ratio
2	phase
A	is the amplitude
ϕ	is the phase
F	is the frequency

Figure 2 — Typical acceleration ratio and phase versus frequency

5.5 Temperature cycle

Make measurements on the test specimen at resonance over a temperature range of − 60 °C to 70 °C, using the following thermal cycle:

- cool the test specimen, mounted on the test apparatus, to − 60 °C;
- allow the specimen to equilibrate to within ± 0,1 °C for at least 12 h before making any measurements;
- after each set of resonance measurements, raise the temperature by 5 °C;
- allow 20 min to elapse after the air temperature has reached the new equilibrium temperature to within ± 0,1 °C before making the next measurement.

6 Analysis of results

6.1 Modulus and loss factor

The real and imaginary parts of the complex Young's modulus are determined from the length, mass and density of the sample, and from parameters obtained from solutions to the wave equation obtained by numerical computation at the experimentally determined resonance frequencies. The wave equation with these boundary conditions has already been described[3],[4]; only the solution will be presented here. The solution to the wave equation consists of two coupled transcendental equations:

$$\sinh\beta(\sin\xi + R\xi\cos\xi) + R\beta\sin\xi\cosh\beta + \frac{\sin\phi}{A} = 0 \tag{2}$$

$$\cosh\beta(\cos\xi - R\xi\sin\xi) + R\beta\cos\xi\sinh\beta - \frac{\cos\phi}{A} = 0 \tag{3}$$

where

A and ϕ	are the measured acceleration ratio and phase (in degrees);
R	is the ratio of the end mass (accelerometer and end block) to the mass of the specimen;
ξ and β	are parameters obtained from the solutions of Equations (2) and (3).

The real part of Young's modulus, E', in pascals, is calculated from:

$$E' = \rho\omega^2 L^2 \left\{[\xi^2 - \beta^2]/[(\xi^2 + \beta^2)^2]\right\} \tag{4}$$

where

ρ	is the density, in kg/m^3;
L	is the length of the bar, in m;
ω	is angular frequency $2\pi f$, with f being the resonance frequency, in Hz.

The loss factor, or tan δ, where δ is the phase angle by which the strain lags the stress, is given by:

$$\tan\delta = E''/E' = 2\xi\beta/(\xi^2 + \beta^2) \tag{5}$$

Solutions to Equations (2) and (3) to obtain parameters ξ and β for each resonance mode are obtained using the Newton-Raphson method. Initial estimates for the two parameters are required to use this method. The analytical solutions for a bar without end mass are used to make these estimates, i.e. with $R = 0$. With this assumption, the initial estimates for the parameters are:

$$\xi = (2n - 1)\frac{\pi}{2} \tag{6}$$

$$\beta = \sinh^{-1}\left(\frac{1}{A}\right) \tag{7}$$

The approximate solutions to Equations (2) and (3) are calculated starting with these estimates and iterating until the values of successive iterations differ by less than 10^{-5}.

NOTE 1 In some other methods, the loss factor is determined from the frequency half-width of the resonance peaks using the quality factor, Q. This approximation is valid only for low-loss materials, where the loss factor is less than 0,1. The method used in this part of ISO 18437 involving the solution to the wave equation is valid for any loss factor.

NOTE 2 The modulus range covered by this method is from 10^4 Pa to 10^{12} Pa, a range that includes common visco-elastic materials. The loss factor range covered by this method is from 0,01 to 5, which also includes common visco-elastic materials.

6.2 Time-temperature superposition

Produce a reduced frequency plot of the modulus and loss factor data in the following manner.

a) Make graphical plots of the real part of the modulus as a function of the base 10 logarithmic frequency for each temperature.

b) Select as the reference temperature, T_0, the temperature for which the real part of the modulus has the greatest frequency slope.

c) Keeping the data at T_0 fixed, shift the real part of the modulus data for the other temperatures, in sequence, along the logarithmic frequency axis until each plot partially overlaps the previous data to obtain the best fit. A best fit is obtained by a least-squares method. The magnitude of the shift required at each temperature is known as the shift factor a_T.

NOTE 1 The real part of the modulus is chosen to be shifted rather than the loss factor because the real part of the modulus is measured more accurately and has less scatter than the loss factor.

d) Shift the loss factor data using the same shift factor that was determined for the real part of the modulus.

NOTE 2 A material for which the above time-temperature superposition is applicable is called thermorheologically simple. A material which fails to superimpose, due to multiple transitions or crystallinity for example, is thermorheologically complex.

e) The resulting plots of real part of the modulus and loss factor as a function of shifted logarithmic frequency at reference temperature T_0 are known as master curves and span a wider range of frequency than measured.

NOTE 3 For a typical resilient material, the shifted frequency range can be as large as 10^{-3} Hz to 10^{9} Hz.

f) Plot the Napierian logarithm of the shift factor, ln a_T, as a function of temperature. Fit these data to the Williams, Landel and Ferry (WLF) equation[5]:

$$\ln a_T = \frac{-c_{10}(T - T_0)}{(c_{20} + T - T_0)} \tag{8}$$

where c_{10} and c_{20} are constants for a given polymer, and subscript zero refers to the reference temperature, T_0, at which the equation is evaluated.

g) The master curves at reference temperature T_0 are shifted to some other reference temperature, T_{ref}, as follows. Determine the logarithmic change in frequency corresponding to the temperature change from T_0 to T_{ref} by evaluating Equation (8) at the temperature T_{ref}. Subtract this logarithmic change in frequency from the values of the logarithmic frequencies corresponding to each of the data points obtained at T_0. The plot using the new frequencies is the master curve for T_{ref}.

NOTE 4 The lower limit in selecting a reference temperature is about equal to the glass transition temperature T_{g}, while the upper limit is about T_{g} plus 100 °C. This upper limit is different for different polymers. The limits exist because the WLF equation is only applicable in the glass transition region.

6.3 Data presentation

Data obtained by the methods of this part of ISO 18437 shall be presented in the form of three graphs:

a) the base 10 logarithmic loss factor versus the base 10 logarithmic real part of the modulus;

b) shift factor versus temperature;

c) master curves of the base 10 logarithmic real part of the modulus and the base 10 logarithmic loss factor versus the base 10 logarithmic frequency at a specified reference temperature. Room temperature may be used for the reference temperature.

NOTE The plot of the logarithmic loss factor versus the logarithmic real part of the modulus includes all data without regard to temperature or frequency. This plot gives an indication of the consistency of the data. Points which do not lie along the curve are suspect and may be ignored. From its inverted “U” shape, this plot is sometimes referred to as a wicket plot.

In order to promote uniformity and ease in interpreting the data at temperatures other than the reference temperature, it is recommended that the master curves of the real and imaginary parts of the modulus and the loss factor be presented as a nomogram using the procedure given in ISO 10112.

6.4 Test report

The test report shall include the following information:

a) a reference to this part of ISO 18437;

b) all details necessary for complete identification of the material tested, including type, source, manufacturer's code number, form and previous history when these are known;

c) if applicable, the direction of any non-uniform feature of the test sample;

d) the date of the test;

e) the shape and dimensions of the test sample;

f) the method of preparation of the test samples;

g) details of the conditioning of the test samples;

h) the number of specimens tested;

i) details of the test atmosphere including humidity;

j) a description of the apparatus used for the test;

k) the temperature sequence used in the test, including the initial and final temperature as well as the rate of linear change in temperature or the size and duration of the temperature steps;

l) a table of the test results including the real and imaginary parts of the modulus and the loss factor versus frequency at each test temperature;

m) the modulus and loss factor versus frequency and temperature plots prepared as specified in 6.3.

Annex A
(informative)

Linearity of vibration resilient materials

In principle, the dynamic properties of a vibro-acoustic isolator are dependent on static preload, vibration magnitude, frequency and temperature.

The assumption of linearity implies that the principle of superposition holds and that the dynamic stiffness at a given frequency is independent of magnitude. For many isolators, this assumption is approximately satisfied when, under the appropriate static preload, the dynamic deformation magnitudes are small compared with the static deformation. However, it should be noted that this depends on the materials of which the isolators are composed, and a simple check should be carried out by comparing the dynamic stiffness characteristics for a range of input levels. If these are nominally invariant, then linearity may be assumed to hold.

For butyl rubber (IIR), Reference [6] presents data for the in-phase component and the phase angle of the dynamic shear modulus as a function of strain magnitude and of the percentage of carbon black. For strain magnitudes smaller than about 1,0 mm/m, the in-phase component and phase angle are hardly dependent on the vibration magnitude. However, a significant decrease of dynamic stiffness is seen when strain magnitudes exceed about 2,0 mm/m, especially for rubber with a high percentage of carbon black.

Therefore, it is important to consider strain magnitudes that occur in practice, and to check whether the test conditions are appropriate for the testing of rubber isolators. For strain magnitudes smaller than about 1,0 mm/m, the assumption of linearity (implying, for example, magnitude-independent stiffness and reciprocity) seems justified.

Hydraulic mounts are increasingly used, especially for automotive applications. This type of isolator may also show a very nonlinear behaviour, i.e. stiffness strongly dependent on vibration magnitude. Because of their two-fold purpose (i.e. damping of low-frequency engine vibration caused by road excitation and isolation of engine-generated structure-borne sound at higher frequencies), appropriate test magnitudes have to be applied for the whole frequency range of interest [7]-[10].

It is sometimes known *a priori* that linearity does not hold. In such cases it may still be advantageous to apply many of the procedures described in ISO 10846-1. Often this will imply that, in addition, special test requirements will be formulated with respect to preloads, signal magnitudes and measuring quantities.

Annex B
(informative)

Time-temperature superposition

It is presumed that a set of valid complex modulus data has been obtained in accordance with good practice. To check the consistency and scatter of the data, plot all data, regardless of frequency or temperature, on a plot of log (loss factor) versus log (modulus). This plot is commonly referred to as a wicket plot. If the data represent a thermorheologically simple material and if the data have no scatter, the data will plot as a single, smooth curve. As unshifted data are plotted in the wicket plot, no part of any scatter in this plot can be attributed to the shifting procedure.

While not required or used in the graphical presentation of data, the wicket plot is useful as a qualitative indication of the scatter of the experimental data. The width of the band of data, as well as the departure of individual points from the centre of the band, is indicative of scatter. Nothing is revealed about the accuracy of the temperature and frequency measurements or about any systematic error. The significance of time-temperature superposition is demonstrated through the concept of reduced frequency.

In general, the complex Young's modulus of a visco-elastic material is a function of frequency and temperature:

$$E^* = E^*(f, T) \tag{B.1}$$

In a thermorheologically simple material, these variables appear only as the product of frequency and a function of temperature known as the relaxation time:

$$E^* = E^*\left[f\tau(T)\right] \tag{B.2}$$

Hence a change in frequency is equivalent to a change in temperature. Consequently, the shift factor can be expressed as the ratio of the relaxation time at temperature T to the relaxation time at a reference temperature T_0:

$$a_T(T) = \tau(T)/\tau(T_0) \tag{B.3}$$

The complex modulus can be written as:

$$E^* = E^*\left[f a_T(T)\tau(T_0)\right] \tag{B.4}$$

and the reduced frequency is defined as:

$$f_\mathrm{R} = f a_T(T) \tag{B.5}$$

The complex modulus can be expressed in two equivalent ways:

$$E^* = E^*[f a_T(T)\tau(T_{0)}] = E^*[f_\mathrm{R}\tau(T_0)] \tag{B.6}$$

so that a modulus value measured at frequency f and temperature T is equivalent to a value at reduced frequency f_R and temperature T_0. The reduced frequency can be much greater than the measured frequency (by a factor a_T) since measurements made as a function of temperature are equivalent to measurements made over a wider frequency range than measured.

The shift factor has been presented here in a formal mathematical manner. The significance of the shift factor function, and the origin of its name, can be illustrated graphically. Consider a log-lot plot of experimental measurements of E' versus frequency plotted as a series of isotherms. Pick one isotherm temperature as the reference temperature. The next highest isotherm can be shifted along the log frequency axis until it partially overlaps the reference isotherm. This process is continued with all the isotherms, in sequence, both higher and lower than the reference. The result is a plot of log E' over a wide range of log reduced frequency values. This plot is known as a master plot. The amount of shift required to produce overlap can be plotted as a function of temperature. Because this function was generated by shifting data, it is known as the shift factor function. A plot of the shift factor can then be compared to the Williams-Landel-Ferry equation[5], [10].

Users of this part of ISO 18437 who are unfamiliar with extending the frequency range of their measurements by time-temperature shifting are referred to ANSI S2.24[11] for further guidance. In ANSI S2.24, the theory sample data, the method of shifting, the resulting shift factor, analytical representation, and the graphical presentation of those data in the form of a frequency-temperature nomogram are presented for a standard material.

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