Measurement, Analysis and Modeling of the Dynamic Properties of Materials

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A new method to measure, analyze, and model the dynamic properties of viscoelastic materials is described. The method is based on the vibrating beam technique (ASTM E756) which has been used for determining dynamic complex modulus properties over wide temperature and frequency ranges. The advantage of this new method is that it is a completely PC based system which contains the data acquisition program for the response of the beam, the finite element analysis program to compute the material properties and the characterization of the properties in term of analytical functions based on the thermorheologically complex viscoelastic model. The output of the curve fitted data is then input to the database of materials library for future use as needed in the analysis of different dynamic systems which incorporate such materials for noise and vibration control. Examples of how this system can be used to build a database on the properties of a variety of materials will be described.

Damping is the term used in vibration and noise analysis to describe any mechanism whereby mechanical energy in the system is dissipated. The damping properties of so-called damping materials, such as elastomeric materials, are usually temperature and frequency dependent, so the experimental determination of damping material properties requires a long and repeating process. The primary objective of this article is to describe an integrated and automated system for the measurement of damping material properties while utilizing standard techniques. The procedure used in this system overcomes some difficulties in traditional analysis methods for the determination of material damping properties and improves the method for presenting and modeling dynamic complex modulus properties.

Usually, the damping capacity of a material can be determined in several ways. The method used in this system is based on the vibrating beam technique (ASTM E756)[1] for determining dynamic complex modulus properties (modulus and loss factor) over wide temperature and frequency ranges. The technique utilizes the elastomeric material to be tested in conjunction with vibrating metal beams either in shear or extension. By sandwiching the material between two metal beams, the properties can be obtained in shear. In addition, by applying the material to the outside of a metal beam, either on only one side or on both sides, the properties can then be obtained in extension.

In principle, any type of beam specimens can be used to make measurements of the dynamic properties of elastomeric materials, however, previous experience has been concentrated mostly on cantilever beams. This is because of the simplicity of the test fixtures for such beams and also because the free end can be simulated properly. However, careful attention must be applied to ensure that the boundary condition at the other end is fully fixed because the flexibility at the clamped end cannot be considered analytically.

In this study, finite element analysis is used in the determination of material properties such that the flexibility of the specimen-fixture interface can be considered. This means that the fully fixed clamped end boundary condition is not crucial for the determination of the material properties. But, careful attention still needs to be applied to ensure that the boundary condition used in the analysis is close enough to that of the actual test. The new system utilizes finite element analysis to model the boundary condition of the test beam and to compute the properties of the material from measured data. The finite element analysis and data acquisition functions are all PC-based and completely automated.

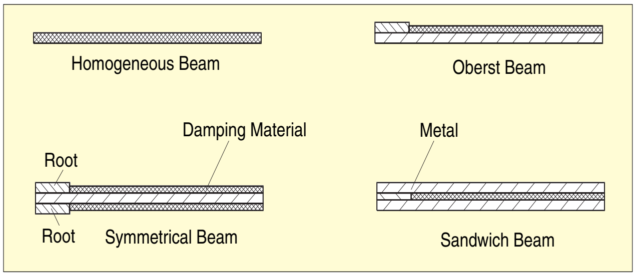

Figure 1. Four different types of beam test specimens.

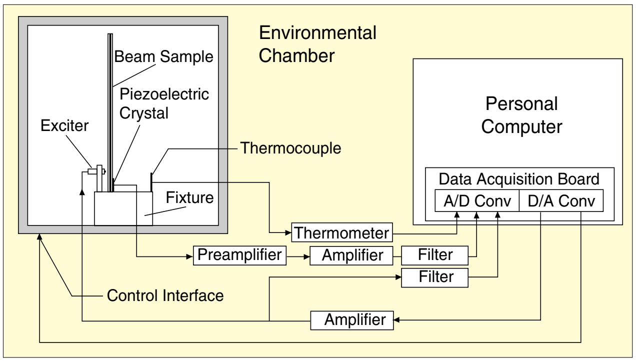

Figure 2. Block diagram of the beam test system, DampFEA^{TM}.

The last feature of the system is characterization of the material properties in terms of analytical functions based on the thermorheologically complex viscoelastic model. This allows the curve fitted data to be input to the database of materials library for future use, as needed, to address noise and vibration problems. The following is a description of the test specimens, test setup, data acquisition and the modeling of properties.

Description of the Specimens

In the vibrating beam technique, an elastomeric material is usually applied to a metal beam so that the measurement is, in reality, of the composite system of two different materials. The dynamic complex modulus properties of the elastomeric material can be calculated from the natural frequencies and corresponding modal loss factors of the composite beam. This system can make measurements and determine material properties for the following four different beam test specimens depending on the properties of the material of interest:

1. The homogeneous beam used for measuring the dynamic properties of metal alloys and composites. These materials are sufficiently stiff to directly use as a test sample without requiring a metal base beam.
2. The Oberst or externally coated beam for measuring the dynamic properties of stiff elastomeric materials in extensional deformation.
3. The symmetrical free layer beam, or modified Oberst beam, with stiff elastomeric material coated on both sides of a metal base beam (also for measuring the dynamic properties in extensional deformation).
4. The sandwich beam for measuring the dynamic properties of relatively soft materials under shear deformation.

Illustrations of the four different test samples are shown in Figure 1.

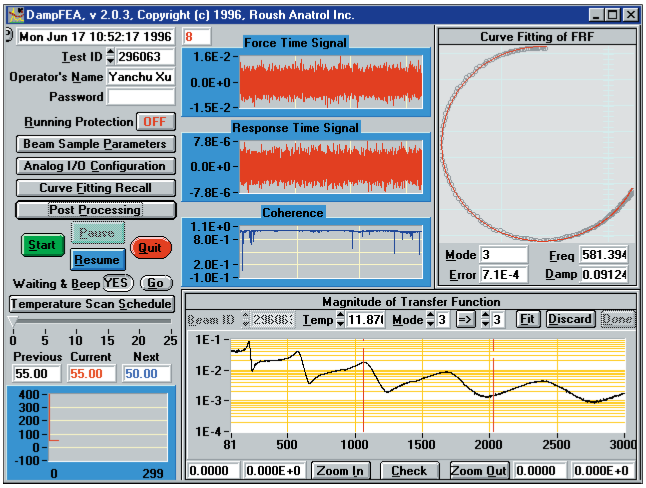

Figure 3. Main panel of DampFEA™.

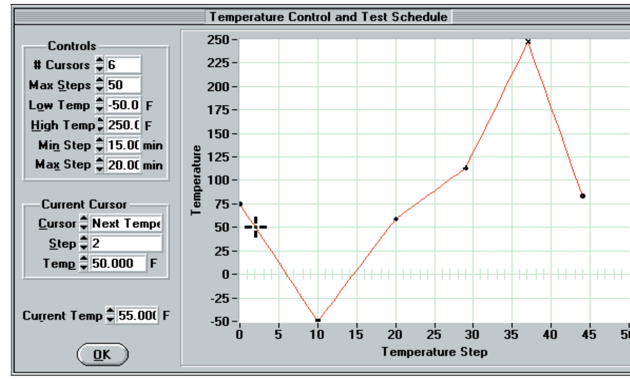

Figure 4. Temperature schedule panel.

Description of the Setup and Data Acquisition

The new system, named DampFEA™, has been developed to conduct automated measurements of the dynamic complex modulus properties of damping materials. A block diagram of the test system is shown in Figure 2. The beam test sample is mounted in a heavy fixture which is carefully designed such that the fundamental natural frequency of the fixture is much higher than the test frequency of interest. Two transducers are usually required for the measurement of the natural frequencies and loss factors of the composite beam. One is needed to apply the excitation force and the other to measure the response of the beam. To minimize extraneous sources of damping, the transducers used are required to be light in weight or noncontacting. Instead of exciting the composite beam at the free end, common in most tests, the fixture allows beam excitation near the clamped end of a cantilever beam. When a noncontacting exciter is used, it will usually apply a static force to the beam. If this static force is applied at the free end of a cantilever beam, it will cause static deformation over the length of the beam which results in uneven preload of the damping material. In particular, if this static force has a force component in the axial direction of the beam, it will change the natural frequencies of the bending modes of the beam. When the exciter moves toward the clamped end of the beam, the errors mentioned above can be minimized.

In order to study the environmental effects on the material properties due to temperature, vacuum and humidity, the fixture is usually mounted inside an environmental chamber. The chamber needs to be controlled so that it can be adjusted to the desired temperature. The actual temperature of the test beam sample is simulated and monitored using a thermocouple which is sandwiched between two metal beams. A PC computer with a plug-in data acquisition board is the center of the system which integrates and automates the whole process for the measurement and analysis of damping material properties.

Software has been developed to perform all necessary process control, A/D and D/A conversion of the measurement signals, digital signal processing, material properties estimation, dynamic complex modulus properties modeling and all post processing. The software is Windows-based with user friendly graphical interfaces, of which the main panel is as shown in Figure 3.

Before starting the measurement, users need to:

1. Input all **beam sample parameters**, which includes selecting one of four different beam test specimens, geometric dimensions, material densities and other information necessary for calculating properties and building a database.
2. Specify **analog I/O configuration**, which includes transducer types used to measure excitation force and beam response, excitation level, excitation type such as random or swept sine, and environmental chamber control interface type such as analog, RS232 or GPIB.
3. Define the **temperature scan schedule** by dragging cursors as shown in Figure 4. This enables users to specify the temperature range of interest, the number of temperature steps desired and how long the software should wait between temperature steps for stabilizing the temperature of the beam sample due to the massive fixture.

These three steps can be in any order or even modified during the test. Tests are identified by their IDs. Users can start a new test which will overwrite any existing files associated with the same test ID or resume a test, which for some reason was stopped previously, to append results to data files of the same test ID.

After the test is started or resumed, the software will automatically send a control signal to the environmental chamber to adjust the temperature according to the temperature scan schedule defined by the user. This is implemented through a D/A converter on the data acquisition board if the chamber has an analog interface or through RS232 or GPIB ports if the chamber has corresponding communication interfaces. The temperature of the test beam sample is always monitored by the software through the data acquisition board. Once the desired temperature is reached and the chamber has stabilized, the software will be triggered automatically to start the measurement of the natural frequencies and loss factors of the composite beam. During the process, the time histories of excitation force and beam response are displayed on the panel. In addition, the transfer function and coherence function between two signals are also calculated and displayed, as shown in Figure 3. Users can monitor measurement parameters and quality.

The natural frequencies and loss factors of the composite beam are obtained from the transfer function. After finishing the dynamic measurement at each temperature, the software searches for the resonance peaks and computes the natural frequencies and loss factors. The resonance peaks of the cantilever beam are usually well separated from each other, so the natural frequencies and loss factors can be estimated with enough accuracy from the corresponding resonance peak without considering coupling with other modes. In this system, the natural frequencies and loss factors are estimated using single peak curve fitting, as shown in Figure 3, instead of the 3 dB down bandwidth method (half power points method). When the 3 dB down bandwidth method is employed, reduced spectral line spacing is required to ensure that frequencies of both the resonance peak and 3 dB down points can be obtained accurately. This is usually implemented by a zoom technique. While the zoom technique can be effective in manual systems, it is often not so in automatic peak seeking. This is especially true when the transfer function near the resonance peak is not smooth. The other drawback of the zoom technique is that the measurement time can be very long because zoom operation might be required many times for each mode. In this system, the accuracy of natural frequency and loss factor identification are provided in two different ways: reduce the required frequency resolution by using peak curve fitting; increase the frequency resolution by using more sampling points. For the PC-based data acquisition system, the number of sampling points

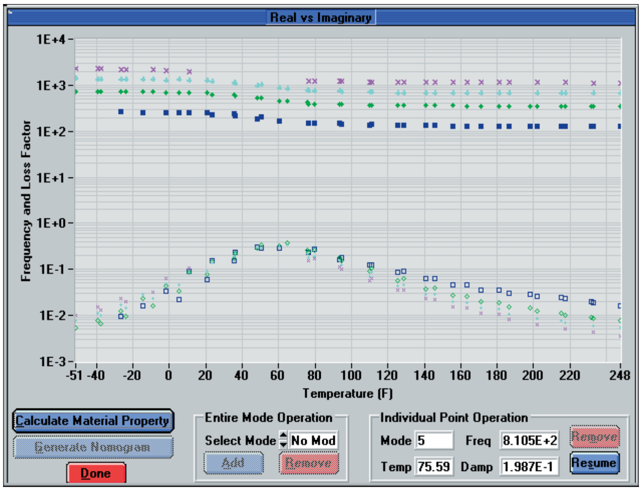

Figure 5. Measured natural frequencies and loss factors of all temperatures.

is virtually dependent on the memory of the computer.

Post processing allows users to check the curve fitting results for natural frequencies and loss factor identification in the dynamic measurement. If any natural frequency or loss factor data point is found to be unreasonable, the user can find the corresponding test temperature and mode by mouse-clicking on that data point and then redo the curve fitting. The composite properties of the beam (modal loss factors and resonant frequencies) are then viewed in terms of temperature for the different modes, as shown in Figure 5.

Finite Element Analysis

One of the important features of DampFEA™ is that finite element analysis is used in the computation of dynamic properties instead of traditional analysis methods. Among the four different beam test specimens, as shown in Figure 1, the homogeneous beam is usually suitable for materials with Young's modulus greater than 10^6 psi (6.98×10^9 N/m^2) because the materials need to be self-supporting. The Oberst or modified Oberst beam can be used for materials with Young's modulus over 10^4 psi (6.89×10^7 N/m^2). Also, the symmetrical sandwich beam can be used for materials with shear modulus below 10^5 psi (6.89×10^8 N/m^2). While formulas for the estimation of the dynamic complex modulus properties of materials in homogeneous beam, Oberst beam and modified Oberst beam configurations have been well developed and can usually give accurate enough results (*provided that the clamped end of the cantilever beam is close to perfectly fixed*), the analysis of sandwich beams has been based on a series of assumptions. They greatly limit its applicable range.

Finite element analysis has been used in the system to overcome the difficulty of handling boundary conditions and to expand the applicable range of sandwich beam test specimens in material properties testing. Finite element modeling can simulate all known boundary conditions: standard boundary conditions, such as fixed end, free end, simply-supported, etc., and also force-displacement relationships. The test system fixture shown in Figure 2 has been carefully designed such that its elastic fundamental natural frequency is much higher than the frequency of interest of the test beam specimens. The flexibility of the beam-fixture interface can be considered to have a static force-displacement relationship, which can be obtained either experimentally or numerically by using the finite element analysis package. This force-displacement relationship of the beam-fixture interface is applied as the boundary condition in finite element analysis of test beam specimens.

A special beam element has been developed to expand the applicable range of sandwich beam tests. The element allows both shear and relative transverse deformation between the outer layers and also includes longitudinal inertia for a sandwich beam. This gives a better simulation when using sandwich beams with soft elastomeric layers. The element also integrates all layers of the composite beam into a single element thereby overcoming the aspect ratio problem encountered in regular finite element modeling of a sandwich beam with a very thin elastomeric layer. Thus the tested beam can be modeled with fewer elements for faster analysis.

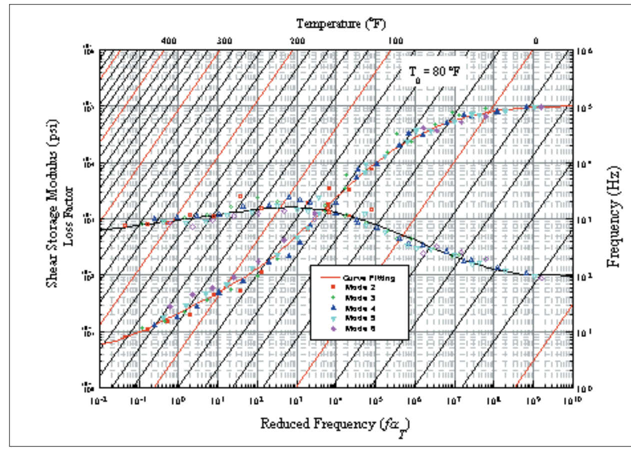

Figure 6. Nomogram of a soft material.

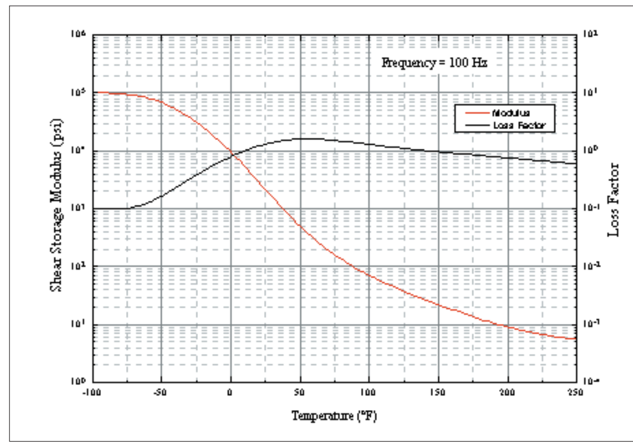

Figure 7. G & η vs. temperature for a fixed frequency.

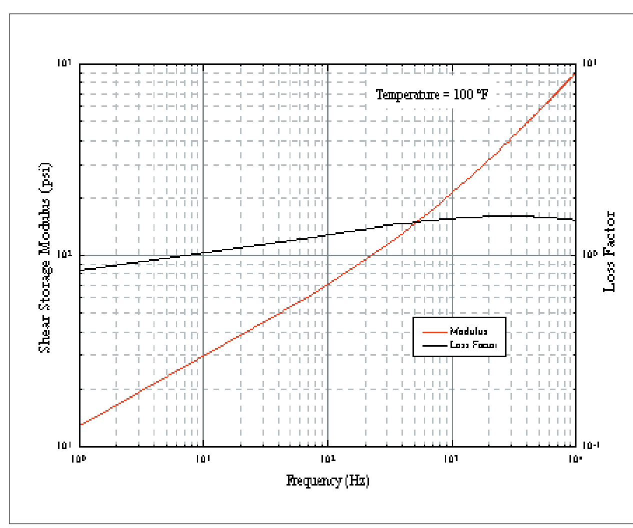

Figure 8. G & η vs. frequency for a fixed temperature.

Modeling of Material Dynamic Properties

Another important feature of DampFEA™ is in presenting and modeling methods for dynamic properties of damping materials. The outputs of finite element analyses are the modulus and loss factor values at different discrete temperatures and frequencies. To model these properties analytically, it is necessary to use the temperature-frequency superposition prin-

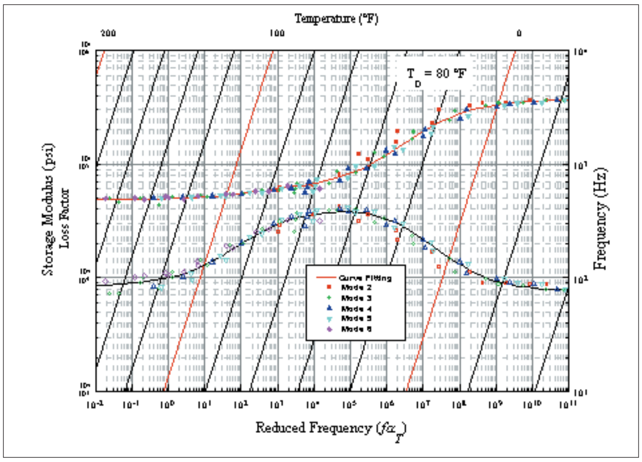

Figure 9. Nomogram of a stiff material.

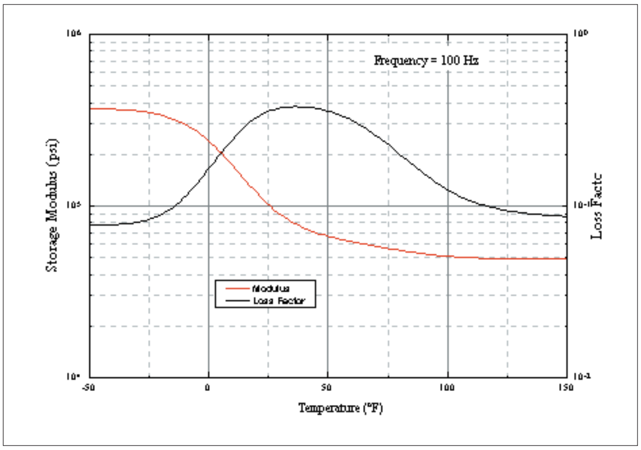

Figure 10. G & η vs. temperature for a fixed frequency.

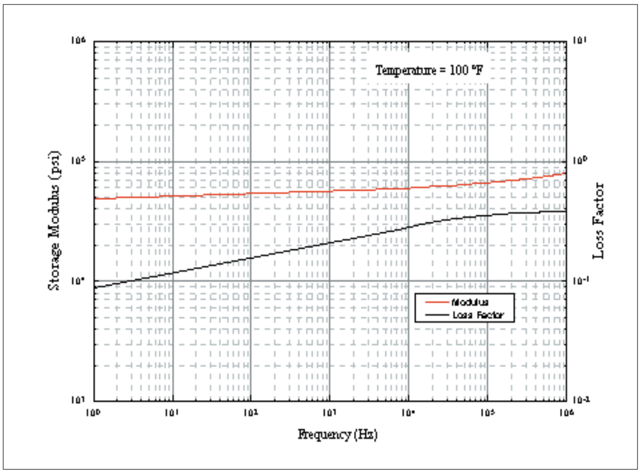

Figure 11. G & η vs. frequency for a fixed temperature.

ciple. This allows for plotting all the data in terms of reduced frequency which is the product of frequency and the shift factor between temperature and frequency for the material. The software computes the shift factor for the material, plots the data in terms of reduced frequency and curve fits the data with an analytical expression as shown in Figure 6.

Instead of using traditional polynomial curve fitting, the technique used in the system is based on the complex modulus $E^*(\omega)$ or $G^*(\omega)$ model developed by Bagley[3] of a thermorheologically complex viscoelastic material which is expressed in the form:

$$E^*(\omega) = \frac{E_\infty(T) + E_0(T) \bullet (\alpha_T(i\omega))^{\beta(T)}}{1 + (\alpha_T(i\omega))^{\beta(T)}}$$

where: $E_0(T)$ and $E_\infty(T)$ are the glassy modulus and the rubbery modulus, respectively; the exponent $\beta(T)$ is the order of the fractional derivative assumed to be a function of temperature; and α_T is the shift factor of the corresponding temperature.

Examples of Measured and Modeled Materials

The data plotted in Figure 6 represent the computed properties from measured data on a sandwich beam using a soft viscoelastic material. The equations of the curve fitted data are stored in the material library along with the necessary information to identify the material and its manufacturer. These equations can then be used in the analysis of different applications as needed or plotted in terms of either temperature or frequency as shown in Figures 7 and 8. Figures 9 through 11 represent similar results for a stiff viscoelastic material.

Summary

The test system developed here is a PC-based, automated system for measuring and analyzing the dynamic complex properties of damping materials. The test method is based on the vibrating beam technique. The system utilizes finite element analysis to model the boundary conditions of the test fixture and compute material properties from the measured data. The thermorheologically complex viscoelastic model is used in curve fitting the material properties which can then be input to the material database for future use.

References

1. "Standard for Measuring Vibration Damping Properties of Materials," American Society for Testing and Materials, E756-80.
2. Ross, D., Ungar, E., and Kerwin, E. M., "Damping of Plate Flexural Vibrations by Means of Viscoelastic Laminates," Structural Damping, Proceedings of ASME, New York, 1959.
3. Bagley, R. L., "The Thermorheologically Complex Material," *International Journal of Engine Science*, Vol. 29(7), 1991.