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Study on the direct measurement of viscoelastic characteristics in the high-frequency range

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Abstract
Viscoelastic (VE) materials are widely used in our daily lives. To utilize VE materials effectively, it is necessary to understand the accurate viscoelasticity over a wide frequency range, especially in the high frequency range. Currently, viscoelasticity is directly measured only in the low-frequency range, and viscoelasticity in the higher frequency is estimated based on the time–temperature superposition (TTS) principle. However, it is generally recognized that estimation by the TTS principle is adequate only for rheologically simple materials in a limited range of temperatures above the glass-transition temperature. In this study, we proposed a shear-type measuring device that can directly measure the shear modulus and tan δ of VE materials. We also proposed a compensation method for the shear deformation mode resonance of the VE material based on the mass value of the moving part to gain a better and more accurate understanding of viscoelasticity in the high frequency range.

Viscoelastic materials, viscoelasticity in high frequency range, measurement device.

1. Introduction

Viscoelastic (VE) materials are widely used in our daily lives. For example, as a contribution to realizing a low-carbon society, fuel-efficient tires with low rolling resistance are being developed. Such tires should have low viscosity in the low-frequency region for reducing rolling resistance and high viscosity in the high-frequency range for ensuring high breaking performance. To design such VE-material products, it is necessary to understand the accurate viscoelasticity over a wide frequency range, especially in the high frequency range.

Currently, viscoelasticity is directly measured only in the low-frequency range (e.g. 10 Hz), and that in the higher frequency are estimated based on the time–temperature superposition (TTS) principle using the Williams–Landel–Ferry equation or Arrhenius equation. However, it is widely recognized that estimation by the TTS principle is adequate only for rheologically simple materials in a limited range of temperatures above the glass-transition temperature. A better understanding of the viscoelasticity in a high-frequency range is required in industrial applications. Therefore, we propose a measuring device that can directly measure the elastic modulus and tan δ of VE materials even in the high-frequency range. In this paper, a shear-type measuring device will be reported as the first step of this research.

2. Measuring device and measuring principle

Generally, hindrance factors for high frequency measurement are low natural frequencies of measuring devices and existence of friction and contact stiffness in the measurement systems. Therefore, we designed a small-sized measuring device with a contact-free design to apply a load and measure the load and displacement.

Figure 1 shows a schematic of the proposed device. The actuator, which can produce a translational force, consists of yokes, magnets, and a coil and bobbin. The moving part, which is the driving component of the actuator, is composed of a moving plate made of aluminium and the coil and bobbin. The coil and bobbin are directly attached to the moving plate with adhesive. VE materials are layered between the moving plate and the fixed blocks. The magnetic flux density in the magnetic circuit is indicated by arrows in Figure 1. When a current is applied to the coil, a translational force is produced, and displacement of the moving plate occurs. The displacement is a shear displacement of the VE materials and is measured by a displacement sensor, which has a wide frequency bandwidth, such as a laser Doppler vibrometer (LDV). The applied force is derived from the current in the coil without using a load cell. Note that the relationship between the current applied to the coil and the translational force of the moving plate must be measured separately. The viscoelasticity of the VE material is determined by measuring the frequency response function (FRF) of the moving plate displacement when a translational force is applied to the moving plate.

Figure 2 shows the measuring device we fabricated. The upper yoke and the upper fixed-block were removed to show its inside structure. We used double-sided tape (NW-10S, Nichiban Co. LTD.) as a measured VE material sample. The size of the VE material was 18.0 mm × 18.0 mm × 0.090 mm.

3. Measurement of viscoelasticity

In Figure 3, the blue lines indicate the measured FRF of the moving plate displacement under the experimental environment of 20.5 °C and 40% R.H. The compliance gain gradually decreased with an increase in frequency. The resonance peak was observed at 24.8 kHz. A gradual phase lag in the low frequency region and a steep 180° phase lag caused by the resonance were observed. These characteristics of the gain and phase are influenced not only by the material properties but also by the resonance mode. If the effect of the resonance mode can be compensated for, then the VE characteristics at higher frequencies can be obtained more accurately. Assuming that the first resonance mode appearing in the measured displacement FRF, *T*(*s*), is the shear deformation mode of the VE material, *T*(*s*) is expressed by the following equation:

$$T(s) = \frac{1}{ms^2 + cs + k} + \Delta T(s) \tag{1}$$

where *m* is the real mass of the moving part, *c* and *k* are the damping coefficient and shear stiffness of the VE material, respectively, *s* is the Laplace transform variable, and $\Delta T(s)$ is the residual compliance. Here, the compensated FRF *U*(*s*), in which the effect of the shear deformation mode of the VE material is compensated for, can be derived using the measured mass of the moving part, $\tilde{m}$ ($\fallingdotseq m$), as the below equation (2):

$$U(s) = \frac{T(s)}{1 - \tilde{m}s^2 T(s)} \tag{2}$$

The measured value of $\tilde{m}$ was 3.87 g. In the frequency range where the gain of $\Delta T(s)$ is negligible, *U*(*s*) can be simplified to the equation below:

$$U(s) \fallingdotseq \frac{1}{cs + k} \tag{3}$$

The reciprocal of *U*(*s*) yields the value of the stiffness of the VE material.

In Figure 3, the red lines indicate *U*(*s*). Based on compensation for the resonance peak at 24.8 kHz, the FRF of *U*(*s*) has no large peak, and the 180° phase lag was eliminated. Note that for a good compensation for the dominant resonance peak, it is necessary that the resonance mode is mainly shear deformation of the VE material without any other elastic deformation. The shear modulus and tan δ derived from *U*(*s*) are shown in Figures 4 and 5, respectively. According to error estimation using the finite element analysis, the measurement error in compliance gain and phase of the *U*(*s*) are less than 10% up to a frequency of 20 kHz.

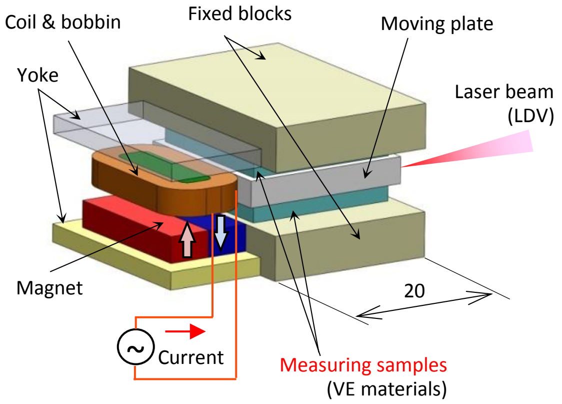

Figure 1. Schematic of the measuring device

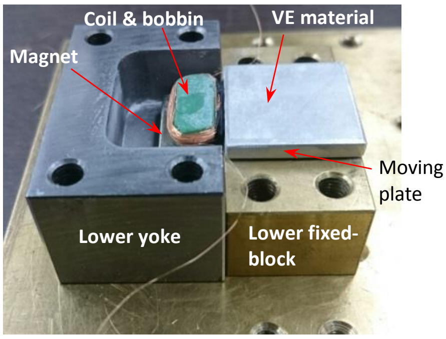

Figure 2. Fabricated measuring device

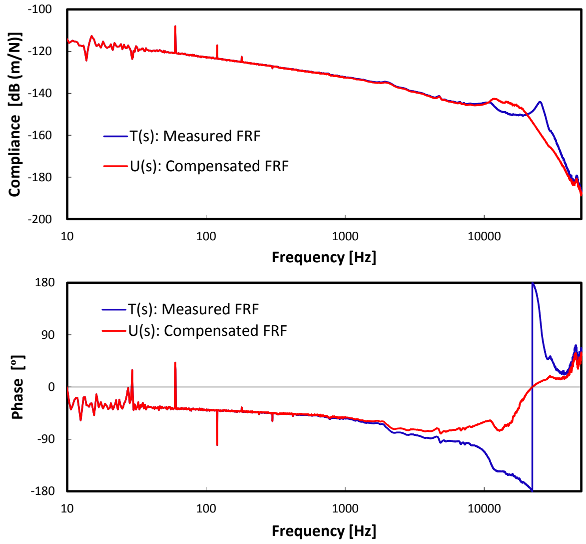

Figure 3. Compliance FRFs

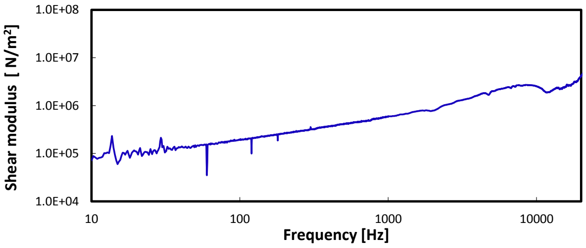

Figure 4. Measured shear modulus of NW-10S

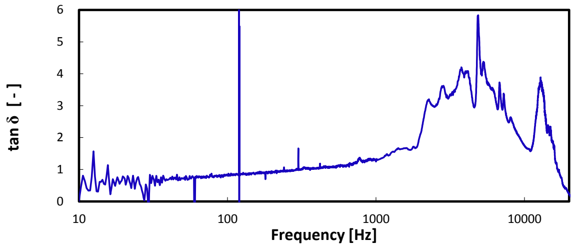

Figure 5. Measured tan δ of NW-10S

4. Conclusion

We developed a device for the direct measurement of viscoelasticity in the high-frequency range. Because the device was designed to have high natural frequencies and to shield it from non-linear behaviours such as friction and contact stiffness so as to eliminate their adverse effects, the viscoelasticity was directly measured without using the TTS principle. We also proposed a compensation method for shear deformation mode resonance of the VE material using the mass value of the moving part to obtain superior viscoelasticity. We measured the viscoelasticity of a double-sided tape (NW-10S) up to 20 kHz directly with the developed measuring device.

Acknowledgement

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Reference

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