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Material Properties

Direct measurement of high-frequency viscoelastic properties of pre-deformed rubber

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ABSTRACT

Rubber is an effective and low-cost material for mechanical vibration suppression because in the glass-transition zone it exhibits high damping abilities. However, analytical predictions of the viscoelasticity of rubber are inaccurate because viscoelasticity depends on the frequency, amplitude and pre-deformation; this inaccuracy impedes the mechanical design of rubber parts. Previously, viscoelasticity measurements under uniaxial deformation have been performed. However, the dominant parameters cannot be clarified in these tests because the strain distribution is not uniform, and the shear strain and hydrostatic pressure are cross-coupled. In this research, a new test method was studied that enabled the direct measurement of the high-frequency viscoelasticity of rubber by independently applying simple shear pre-strain and hydrostatic pressure. The viscoelasticity of nitrile rubber was measured using this method at frequencies from 200 Hz to 2000 Hz under shear pre-strain and pre-compression. The results showed that hydrostatic pressure had a much larger influence than shear pre-strain. The hydrostatic pressure should be considered as a more essential parameter than the stretch or strain in this material.

1. Introduction

Elastomers are ideal materials for vibration suppression because they are low in cost with high internal friction. They are utilized for various supporting structures, such as high-speed bearings of turbo compressors that experience self-excited vibrations. These vibrations are effectively suppressed when the bearings are supported elastically with elastomeric O-rings [1–8]. Rubber is also utilized for vibration isolators in the payload attachment of solid-propellant launch vehicles [9], in which elastomer sheets are subjected to both the static acceleration force of the payload and high-frequency vibrational forces excited by the combusting rocket motor. Solid propellant itself is also a composite rubber that exhibits highly viscoelastic behavior, contributing to the structural damping effect of instable combustion oscillations [10,11].

The dynamic properties of these parts are usually obtained experimentally using actual components, because it is difficult to calculate and predict the precise dynamic properties for the mechanical design of bearing supports or the other components made of filled rubbers such as nitrile rubber (NBR), which contain particles in the rubber matrix and show viscoelastic behavior with significant deformation dependence [12,13]. According to the comprehensive measurements of the dynamic properties of O-rings, squeeze, temperature and vibration amplitude have significant effects [14]. The squeeze produces pre-deformation in the O-ring. Therefore, it is important to clarify the effect of pre-deformation on the dynamic constitutive law of rubbers.

The strain tensor can be decomposed into diagonal and deviator tensors. Because the Poisson's ratio of rubber is nearly 0.5 (almost incompressible), the trace of the diagonal term (volume change) is quite small. Therefore, not only the deviator tensor, but also the diagonal tensor, are in almost pure shear. In other words, any kind of deformation of an incompressible material consists only of shear deformation. Hence, it can be stated that the shear viscoelasticity and the effects of pre-deformation are all we need to predict the dynamic properties of rubber.

Dynamic mechanical analysis (DMA) measurements of NBR under uniaxial tension and compression revealed that the stiffness and damping were monotonically reduced by the stretch λ for both compression ($\lambda < 1$) and tension ($\lambda > 1$) [15]. Uniaxial deformation changes not only shear strain but also hydrostatic pressure. In terms of shear strain, uniaxial compression and tension are equivalent cases. Although the sign of the shear strain is opposite for the two cases, the polymer chains of the rubber are stretched in both cases. The stretching of polymer chains is minimized when $\lambda = 1$. If the stiffness and damping

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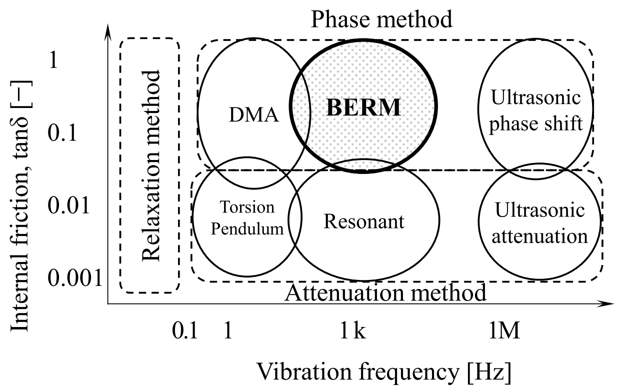

Fig. 1. Classification of measurement methods of viscoelasticity. The relaxation method is static, while the others are dynamic.

are both reduced by polymer chain stretching, then both should have a peak at $\lambda = 1$. However, their monotonic decrease with increasing λ suggests that the hydrostatic pressure is dominant in the viscoelasticity of the material. It is hypothesized that the uniaxial deformation dependence of viscoelasticity is caused by changes in hydrostatic pressure. Indeed, the viscoelasticity of rubber in the glass-transition zone depends on both the strain and hydrostatic pressure [16]. However, this hypothesis cannot be verified with existing test methods because shear strain and hydrostatic pressure are cross-coupled in uniaxial deformation.

Many measurement methods for viscoelasticity and the frequency dependence thereof have been developed. For large strains, the split-Hopkinson pressure bar (SHPB) method [17] can be used to investigate the dynamic properties at high strain rates exceeding $10^3\,s^{-1}$. As for small-amplitude cyclic strain, dynamic properties are characterized by a complex modulus. The appropriate methods are classified by the applied frequency and tanδ of the material, as shown in Fig. 1. DMA is the most commonly used method and defined as standard (ISO 4664–1 "Non-resonance method") for any elastomer whose tanδ is greater than 0.01 in general. The influence of pure shear strain on the viscoelastic behavior of rubber was investigated by using a servo-hydraulic machine [18]. In their experiments, periodic deformation was applied and the shear force was obtained, hence the method can be classified as DMA. However, DMA is applicable only for low frequencies below 100 Hz, because of the limitation of the natural frequencies of general load cells. High-frequency viscoelasticity at frequencies exceeding 1 kHz has been obtained indirectly by shifting the frequency with a shift factor based on the Williams–Landel–Ferry (WLF) equation [16]. However, this indirect measurement is limited in accuracy because of the non-constant shift factor, because only certain polymers are thermorheologically simple [13]. A direct measurement method is necessary for such materials.

Darlow and Gupta et al. [6,19] developed a direct test method called "Base Excitation Resonant Mass (BERM)," which was suitable for measuring dynamic properties at higher frequencies reaching 1000 Hz. In BERM, the load cell of a DMA apparatus was replaced by a resonant mass and a displacement sensor. The applied force was obtained as the inertial force of the resonant mass. The method is accurate only near the natural frequency of the system, as determined by the resonant mass and the stiffness of the specimens. The natural frequency can be adjusted by changing the size of the resonant mass. Various conditions can be applied to the specimen, including uniaxial compression, simple shear, and O-rings. However, in the original BERM, static shear pre-strain and hydrostatic pressure could not be applied independently.

The authors have developed the PBERM (Paired Base Excitation Resonant Mass) method [20], in which two pairs of specimens sandwiched the resonant mass. Static simple shear pre-strain could be applied to the specimens independently of the hydrostatic pressure by separating the pair of clamps. However, this approach lacked consideration of the relaxation of hydrostatic pressure after pre-compression. In this study, we discuss the calculation methods for determining the viscoelastic model parameters and the measurement accuracy of this method. An experimental study was performed to investigate the effects of relaxation after pre-compression. A three-element viscoelastic model was developed and implemented in the finite element method (FEM).

2. Measurement of shear properties

2.1. Experimental apparatus

Fig. 2 shows a schematic representation of the PBERM test section. Two pairs of upper clamps (1, 2) and lower clamps (3, 4) sandwich the resonant mass and four sheets of test material (Formula in Table 1). The

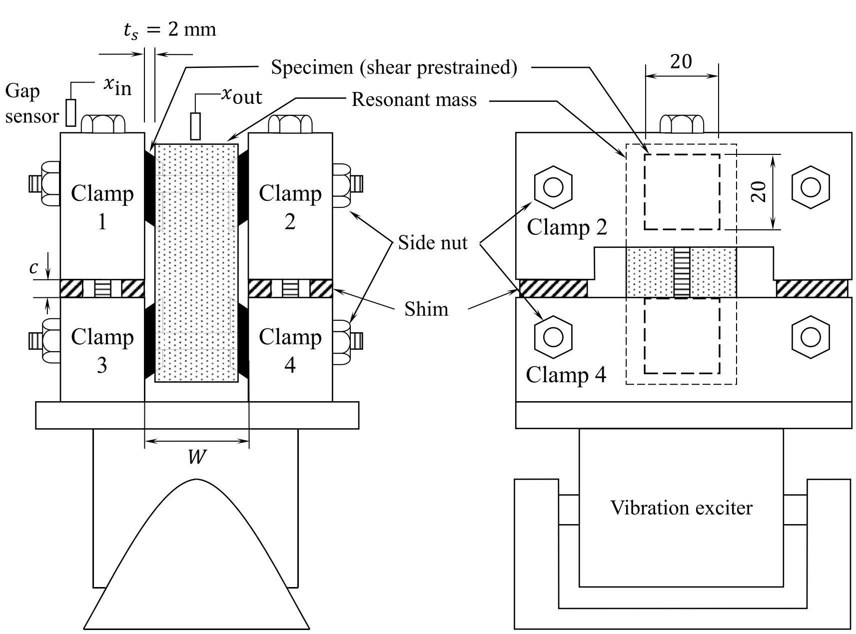

Fig. 2. Schematic of PBERM method. Shear pre-strain γ can be applied by inserting shims of various thickness. Pre-compression ε can be applied by tightening the side nuts.