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Viscoelasticity evaluation of rubber by surface reflection of supersonic wave

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Abstract

The main characteristic of rubber is a viscoelasticity. So it is important to research the characteristic of the viscoelasticity of the high frequency band for the friction between a rubber material and the hard one with roughness, for instance, the tire and the road. As for the measurement of the viscoelasticity of rubber, DMA (dynamic mechanical analysis) is general. However, some problems are pointed out to the measurement of the high frequency band by DMA. Then, we evaluated the viscoelasticity characteristic by the supersonic wave measurement. However, attenuation of rubber is large, and when the viscoelasticity is measured by the supersonic wave therefore, it is inconvenient and limited in a past method by means of bottom reflection. In this report, we tried the viscoelasticity evaluation by the method of using complex surface reflection coefficient and we compared with the friction coefficient under wide-range friction velocity. As a result, some relationships had been found for two properties. We report the result that character of viscoelasticity of rubber was comparable to friction coefficient.

Keywords: Viscoelasticity; Complex surface reflection; Friction coefficient; Tire; Supersonic wave

1. Introduction

It is understood that there is a deep relationship between the friction of the tire and the viscoelasticity, especially loss tangent $\tan\delta$ being researched for years [1–3]. Moreover, it is said that the friction frequency are the high frequency band (10^2–10^6 Hz). However, a general viscoelasticity evaluation method DMA (dynamic mechanical analysis) is limited in the low frequency (10^1–10^2 Hz) measurement. For the viscoelasticity evaluation at the high frequency band, it was necessary to do the time–temperature conversion that had the problems like a conversion error margin or a temperature increasing time. Therefore, it is not possible to measure in the state of actual use, so that the measurement was limited in the laboratory. For the supersonic, a vibration of the high frequency band, viscoelasticity measurement of the solid polymer, a basic theory and measurement result used the rubber sample in the water tank were reported [4,5]. However, the measuring method for the real shape and actual use rubber commodity had not established. Moreover, the relationship between the supersonic wave viscoelasticity and the friction coefficient was not examined.

Authors compared the friction coefficient of rubber and paper at a wide-range sliding velocity with $\tan\delta$ by DMA and the supersonic wave, and qualitative correlation was reported [6,7]. In these reports, $\tan\delta$ was calculated from the attenuation coefficient and the acoustic phase velocity of rubber by the bottom reflection method using the bottom reflection wave propagation through the inside of the rubber sample. However, because of rubber was the well known

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high attenuation material, there were the problems that the reflection wave signal from the bottom of sample cannot obtain enough strength, an enough flatness and reflectivity were necessary for the sample bottom in a actual use.

To solve such problems, we are able to remember the method that complex modulus is calculated by complex reflection coefficient measured by the reflection wave on the surface of the sample. As the viscoelasticity measuring method using surface reflection coefficient, the oblique angle incidence SH wave method using quartz buffer has been researched since 1940s [8–11]. However, measuring object was mostly a liquid and there were few reports about a solid material such as cured rubber.

The SH wave must be chosen in this oblique angle incidence method for reduction the mode transformation error margin. However, in the propagation of the shear wave such as SH wave, it was difficult to request enough reproducibility in the surface reflection method by the phase difference of the reflection wave from the boundary of sample and buffer, because the bonding accuracy of the solid sample and solid buffer have a big influence on the measurement accuracy.

To solve the problem of the surface reflection wave viscoelasticity measurement method, we have evaluated the surface reflection method by a longitudinal wave vertical incidence. We think the mode transformation may be little by means of the vertical incidence, and a longitudinal wave also makes the bonding easier. We hope this method will be able to be applied to the viscoelasticity measurement for actual use shape of rubber product like a tire.

In this paper, we report our study about relationship between viscoelasticity and friction by comparing the supersonic viscoelasticity measurement method using longitudinal vertical incidence surface reflection wave from boundary of buffer and sample with the frequency property of friction coefficient of rubber.

2. Theory and experimental apparatus

2.1. Examination material

The measuring samples that were mixed the silica particle with three varieties of matrix rubbers of butadiene rubber (BR), styrene butadiene rubber (SBR), and polynorbornene rubber (PNR) were prepared. BR and SBR are popular materials for the tire. PNR was popular material for the paper feeding roller. As you can see in Table 1, one of the viscoelastic parameter the glass transition temperature T_g measured by DSC (differential scanning calorimetry) for each rubber samples shows a big different value.

2.2. Surface reflection supersonic wave viscoelasticity measuring method

The schematic of the supersonic viscoelasticity measuring method composition using the surface reflection wave is shown in Fig. 1. Supersonic transducers were the one for NDT (non-destructive-testing), total band of 0.5–100 MHz. The pulsar receiver was also the one for NDT, generate pulse wave form. Wave form U_A of surface reflection wave that was obtained through the oscilloscope was analyzed by fast Fourier transform with the personal computer. The absolute value of reflection coefficient from the power spectrum and the phase delay θ from the phase spectrum were calculated standardized based on the reflection with air U_{A0}.

Table 1
Examination material

Group	Hardness (JIS-A)	Filler[a]	T_g, (°C)
BR	40	Si	−105
SBR	40	Si	−50
PNR	40	CB	−4

[a] Si: silica, CB : carbon black.

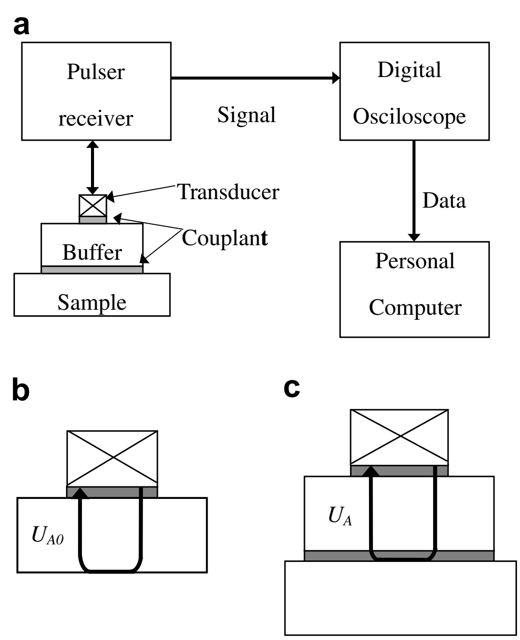

Fig. 1. Schematic of measurement apparatus for supersonic viscoelasticity evaluation by surface reflection.

$$R = \frac{U_A}{U_{A0}} = \frac{A e^{i\theta_A}}{A_0 e^{i\theta_{A0}}} = |R| e^{i\theta} \quad (1)$$

$$|R| = \frac{|A|}{|A_0|} \quad (2)$$

$$\theta = \theta_A - \theta_{A_0} \quad (3)$$

Complex reflection coefficient R was calculated by Eqs. (1)–(3).

Storage modulus L', loss modulus L'' and loss tangent $\tan\delta$ was calculated by Eqs. (4)–(6).

$$L' = \frac{Z^2_{\text{Buffer}}}{\rho} \frac{(1-|R|^2)^2 - 4|R|^2 \sin^2\theta}{(1+2|R|\cos\theta + |R|^2)^2} \quad (4)$$