Broadband dynamic parameters measurement by longitudinal vibration testing using pulse wave

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ABSTRACT

Paper presents a method to measure the dynamic parameters of viscoelastic material bar by the longitudinal vibration testing in a wide frequency range. In the measurement, one end of the bar is driven by a transducer using a pulse wave and the other end is allowed to move freely. The vibration velocity of the free end of the bar is measured by a laser Doppler vibrometer. The dynamic parameters are calculated from the vibration velocity ratio between the long bar and the short bar over a wide frequency range since the driven signal of the pulse wave is a broadband signal.

Keywords: Viscoelastic material, Dynamic parameters, Transmission I-INCE Classification of Subjects Number(s): 72.7

1. INTRODUCTION

Viscoelastic materials are widely used in the vibration noise control engineering.Knowledge of the dynamic elastic properties of such materials, as a function of temperature and hydrostatic pressure, is essential to be used for designing the most effective structure of vibration and noise reduction.

Several methods have been used to measure the dynamic parameters of viscoelastic materials, such as forced oscillatory measurements, resonance measurements, dynamic mechanical analyses etc.(1-5).

F.M.Guillot et al.(6, 7) tested the vibration characteristics of the material utilizing laser Doppler vibrometers in a pressure vessel. The elastic modulus of the material is obtained according to resonance measurements and wave-speed measurements in different temperature, different frequency and different hydrostatic pressures. Hongwei Li (8) built a testing system based on the method by Guillot ed al. But in the process of the wave-speed measurements, the lateral motion produced by the longitudinal wave is submerged by the bending motions, which lead to measurement error. It should be noted that the measurement signal is sweep frequency signal or pulse modulated sine in above methods.

R.L.Willis et al.(9, 10) inversed the Young and shear dynamic moduli of the viscoelastic materials under variable temperatures and hydrostatic pressures by combining the experimental measurement and finite element analysis.But the inversion code does not converge well under some conditions.

In 2012, Xiping He et al.(11) proposed a forced longitudinal oscillatory measurements to determine Young's modulus of the viscoelastic sample. They adopted the broadband short pulse signal to drive the shaker and measured the free end longitudinal vibration of the long bar and short bar. After the amplitude ratio of broadband frequency range was acquired using the 3dB bandwidth of the curve, the storage and viscous modulus of the sample bar can be obtained.

This paper present a new method improved on the basis of wave-speed measurement proposed by Guillot(6, 7),which can obtain the dynamic parameters by fewer experiments.Firstly,a controllable pulse wave is generated and is used as testing signal. Some details about the pulse wave generation can be refered (12-15). Secondly, a long bar and a short bar are driven by a transducer using the pulse wave respectively. Thirdly, the vibration velocity ratio between the long bar and the short bar is measured and the parameters can be calculated by data processing over a wide frequency range.

2. WAVE-SPEED MEASUREMENTS(6)

Let us consider a homogeneous bar of density ρ and length L,with a constant cross section and no mass attached to its free end (Figure 1). One end of the bar is driven with a short burst consisting of a gated sinusoidal signal. In this case, monitoring the propagation of this burst allows one to measure both the wave speed and the attenuation in the material.The wave-speed magnitude *c* is obtained in a straightforward manner by measuring the time necessary for the burst to travel a distance ***d*** along the sample according to

$$c = \frac{d}{t_{x+d} - t_x} \tag{1}$$

Where t_{x+d}-t_x is the time necessary for the burst to travel a distance ***d***.

The signal attenuation α is obtained from the change in signal amplitude over the same distance according to

$$\alpha = \frac{1}{d}\ln\left(\left|\frac{u(x,t)}{u(x+d,t)}\right|\right) \tag{2}$$

Due to this article focuses on the broadband frequency testing, the wave-speed magnitude *c* and the signal attenuation α are calculated in the frequency domain. In MATLAB, signals are subjected to a fast Fourier transform. According to the amplitude spectrum $U_1(\omega)$, $U_2(\omega)$ and the phase spectrum $\varphi_1(\omega)$, $\varphi_2(\omega)$,the signal attenuation α can be expressed as

$$\alpha(\omega) = \ln\left(\left|U_1(\omega)/U_2(\omega)\right|\right)/d \tag{3}$$

The time necessary for the burst to travel a distance ***d*** can be expressed as

$$\Delta t(\omega) = \left(\varphi_1(\omega) - \varphi_2(\omega)\right)/\omega \tag{4}$$

The wave-speed magnitude *c* is calculated according to

$$c(\omega) = d/\Delta t(\omega) \tag{5}$$

Then we plug α and *c* in the following functions to obtaine the dissipation factor tan(δ) and the storage modulis $E^{'}$

$$\tan(\delta) = \tan\left[2\sin^{-1}\left(\frac{\alpha c}{\omega}\right)\right] \tag{6}$$

$$E^{'} = E\cos(\delta) = \rho c^2 \cos\left[2\sin^{-1}\left(\frac{\alpha c}{\omega}\right)\right] \tag{7}$$

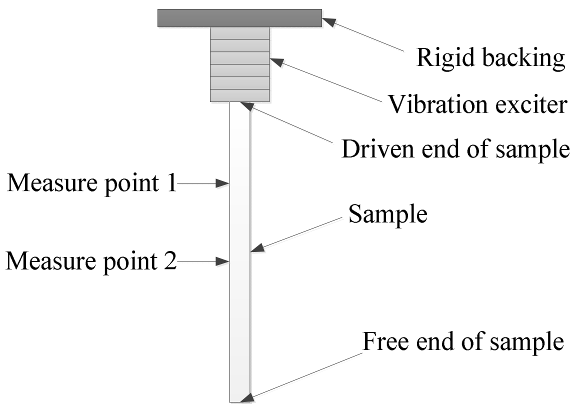


Figure 1 Wave-speed measurements diagram

3. MEASUREMENT PROCEDURE

3.1 Experimental apparatus

The principle of the wave-speed measurements is represented schematically in Figure 2.The computer outputs the drive signal we designed, then it is imported to vibration exciter (JZ-2A) through poweramplifier(BK2716). The vibration exciter can generate the broadband short pulse signal and make the viscoelastic sample bar vibrate longitudinally. The vibrations of long bar and short bar free end are measured by a laser Doppler vibrometer(PDV-100).The experimental system can make sure the stimulating and collecting synchronize.

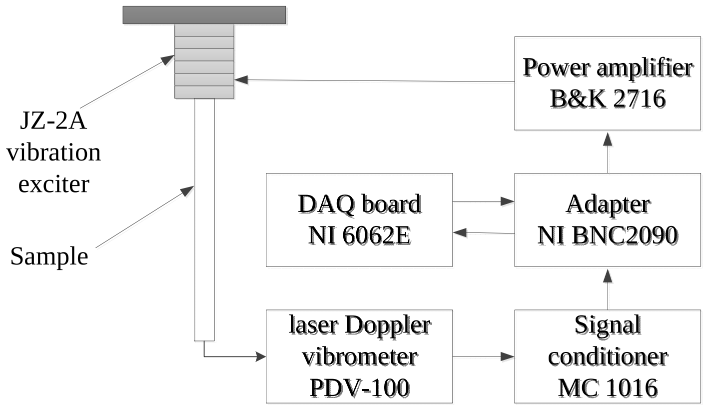
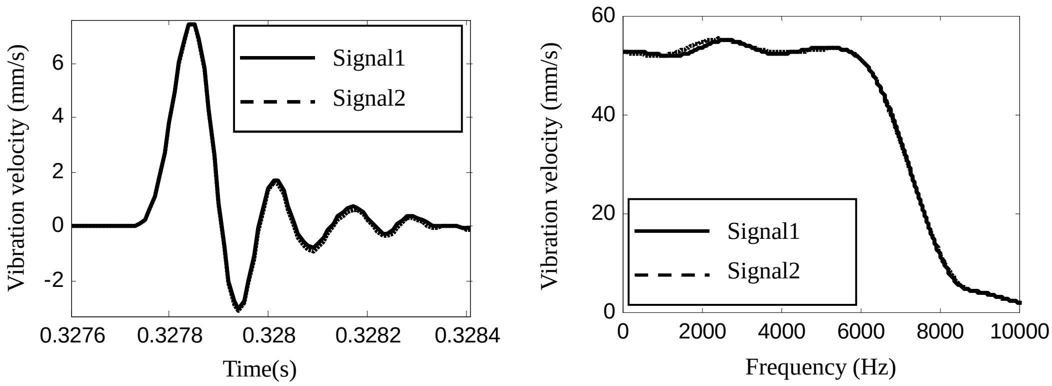


Figure 2 Schematic of the experimental apparatus

3.2 Measurement procedure

To measure the dynamic parameters of the viscoelastic material,the drive signal needs to be enough wide in frequency-domain.For the complex modulus of the viscoelastic material changes with the chang of frequency,the components of different frequencys have different propagation speeds. So we need the drive signal enough short in time-domain, otherwise the wave form of the signal could be streched in time-domain, which is bad for measurement. In our experiment, we use the Butterworth broadband short pulse as the drive signal. As seen in Figure 3, the duration of the signal is only 8ms, and its upper cutoff frequency is 7kHz.The two generations show the method repeatable well.



(a)Time domain signals (b) Amplitude spectrum

Figure 3 Butterworth broadband short pluse generated by vibration exciter

Using the drive signal, we drive the two sample bars with different lengths(As seen in Figure 4).The length of the long bar is 204.5mm and the short bar is 161mm.Both of the two bars’density is 1458kg/m^3.By comparing and researching many experimental results, we find that the signal to noise ratio is enough if the difference of bar’s length is more than 30mm and less than 50mm. The longitudinal vibration velocitys on the free ends of the two bars are measured by a laser vibrometer, as seen in Figure 5. The storage modulus and the loss factor of the material in frequency-domain can be calculated according to function(6) and function(7).

According to our simulation, the sample bar we used in experiment is a kind of viscoelastic material with great attenuation. Its loss factor increase with frequency. It is proven that the high frequency vibration signal above 1k Hz is almost completely decayed when it arrives at the free end. So we can consider the vibration of the sample bar at the free end only contains the direct wave for those frequencys higher than 1k Hz.

Figure 4 Viscoelastic long and short stick

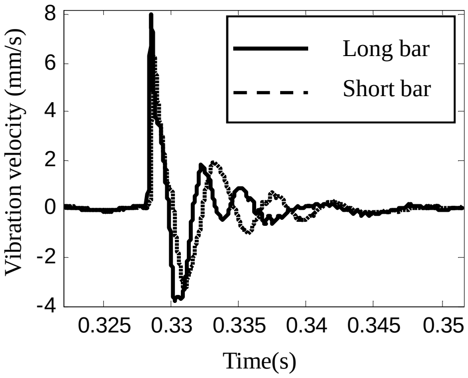


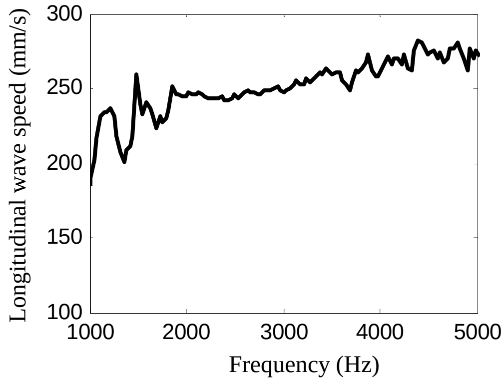
Figure 5 Longitudinal vibration velocity at the free ends of bars with different lengths

3.3 Measurement result analysis

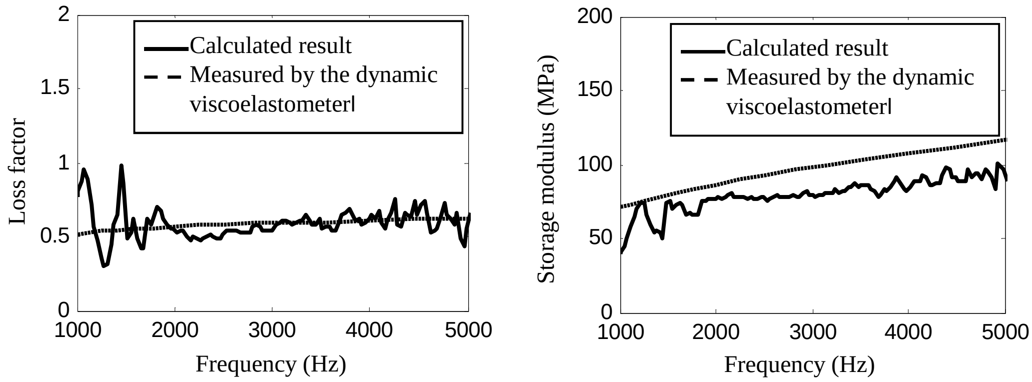
Using the wave-speed measurement based on the two bars with different lengths, we need only to measure the longitudinal vibration of the two different sample bars respectively with a laser vibrometer. Then we can calculate the parameters in the frequency range from 1k Hz to 5k Hz in several minutes(Figure 6).While, in the traditional wave-speed measuremen, we need to measure the lateral vibration. But the lateral vibration is easy to be submerged by the bending motions, so we must use 4 laser vibrometers at least. Besides, the drive signal used in the traditional wave-speed measurement is the pulse modulated sine wave. If we need the parameters at several frequencys, we need to repeat the measurement for many times, which is obviously not convenient.

The experimental system is established at room envionment without temperature adjusting device. So that it is difficult for us to ensure the environmental conditions are the same as that measured by viscoelastic meter.The parameters measured by viscoelastic meter as shown in Figure 6 is obtained by the time temperature equivalence principle.

As shown in Figure 6(b) and Figure 6(c), the storage modulus and loss factor calculated in this paper and the parameters measured by viscoelastic meter are respectively approximate and they have the same varying trend.



(a) Longitudinal wave speed



(b) Loss factor (c) Storage modulus

Figure 6 Solid lines are used for the results we calculate using the method we propose in this paper and dashed lines are used for the parameters measured by the dynamic viscoelastometer

4. CONCLUSIONS

A broadband method is proposed to measure the dynamic parameters of viscoelastic material bar by the longitudinal vibration testing in a wide frequency range.

Using pulse wave generation technique and the laser Doppler vibrometer, we generate a vibration pulse with its waveforms controllablely and repeatablely.At room environment, we drive the fixed end of the two bars with different lengths using a broadband short pulse.Keeping stimulating and collecting synchronize, then we use a laser vibrator measure the longitudinal vibration velocity in the free end of the two bars respectively. The dynamic parameters can be calculated from the vibration velocity ratio and the phase difference between the long bar and the short bar over a wide frequency range.The results show that, in the frequency range from 1k Hz to 5k Hz, the storage modulus and the loss factor calculated directly agree well with the parameters obtained by the dynamic viscoelastic meter, which verify the effectiveness and accuracy of this method.

One thing to be noted is that the precondition of the method we proposed in this paper is the longitudinal vibration in the free end of the bar can be approximately the direct wave.This condition can be met for the viscoelastic material used in this paper. Otherwise, it is needed to analysis the effective frequency range of this method.

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