

Measuring vibration characteristics at large amplitude region of materials for high power ultrasonic vibration system

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Abstract

This study proposes a method of estimating the mechanical quality factor of materials for high-power ultrasonic vibration systems under large vibration amplitude conditions. The quality factors of several metals as well as some polymers are measured by this method. In this method, the quality factor is calculated as the ratio of the reactive energy stored in a specimen to the dissipated energy. The dissipated energy is estimated from the input/output mechanical energy to the specimen by measurement of the vibration intensity, while the reactive energy is measured as the kinetic energy of the vibration. Then, the quality factor for the specified part can be extracted using this method. In this report, quality factors for torsional vibration were measured at about 30 kHz as functions of the vibration strain. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Large amplitude vibration; Quality factor; Torsional vibration; Transducer; Vibration system

1. Introduction

Metals are widely used in high power ultrasonic vibration systems such as transducers, horns and vibration converters [1]. It is essential for such applications that the materials be efficient in vibration transmission, because vibration loss causes heat and a temperature rise which sometimes determines the maximum usable vibration amplitude in practice. Hence, the choice of material is one of the major considerations of the design. Generally, the vibration loss is a function of the vibration strain, and one should consider the loss in the high vibration amplitude region where the vibration system is actually used.

Quality factor (Q -factor or mechanical Q) is a popular indicator for measuring the amount of vibration loss. However, it is difficult to estimate the Q -factor of a specified part of the vibration system from the response observed at the electrical port, since a high power ultrasonic vibration system contains piezoelectric ceramics (PZT), and contact surfaces of two components with a bolt, and sometimes adhesive, in the joints. PZT has a much lower Q -factor than metals, and it masks the

vibration properties of metal components. Contacting conditions between the two parts are also uncertain factor. In addition, the time domain technique by the impulse response is not suitable for measurement at high vibration amplitude levels.

This paper presents a new method to evaluate the Q -factor of material itself without the effect of other parts of the vibration system at high vibration amplitude level. It is based on the general definition of the Q -factor: the ratio of the stored reactive energy to the dissipated energy. The reactive and dissipated energy are calculated from the vibration distribution. An instrumentaion for this method is developed, and several measurements are demonstrated for torsional vibration. Although torsional vibration is beginning to be used in various high power applications, such as ultrasonic motors, welding and other processing techniques [2,3], we have little information about the properties in the large amplitude region.

2. Principle of the measurement

Here, let us assume a portion of a vibrating bar as shown in Fig. 1. Torsional vibration is excited along the z -axis, and the vibration energy flowing across the

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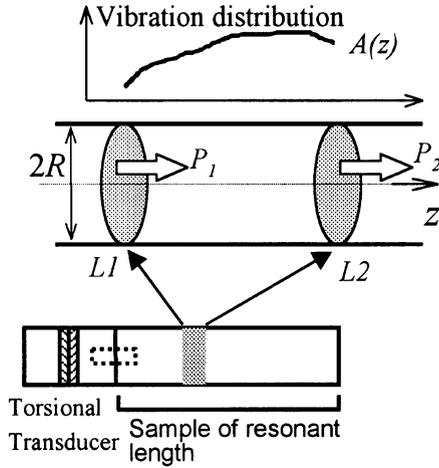


Fig. 1. Measurement of the Q -factor based on the general definition.

surface L1 and L2 are P_1 and P_2 , respectively. The Q -factor is defined generally as a ratio of the maximum reactive energy W_k to the dissipated energy W_d for a period:

$$Q = \frac{2\pi W_k}{W_d}. \quad (1)$$

If the vibration velocity at the outer surface $A(z)$ is measured, we can calculate the kinetic energy for torsional vibration which gives W_k :

$$\begin{aligned} W_k &= \int_{L1}^{L2} \int_0^{2\pi} \int_0^R \frac{1}{2} \rho \left(\sqrt{2} \frac{A(z)}{R} r \right)^2 r dr d\theta dz \\ &= \int_{L1}^{L2} \frac{\pi}{2} \rho R^2 A^2(z) dz, \end{aligned} \quad (2)$$

where $A(z)$ is measured as the root mean square value. ρ and R are the density and the radius of the specimen.

Next, the total dissipated energy is calculated as the change in the energy flow $P_2 - P_1$ along the axis, assuming that the sound emission from the side wall of the bar is included in the loss. P_1 and P_2 , are defined as the flux of energy in vibratory motion [4], and the time average of instantaneous flux or the real part of complex flux corresponds to the effective energy flow [5]. Using this technique, a small amount of energy flow conveyed by the progressive wave component can be detected under the highly standing wave state. The effective power flow per unit area I_z is calculated with the circumferential shear stress $T_{\theta z}$ and the vibration velocity v_θ as:

$$I_z = \text{Re}[T_{\theta z} v_\theta^*] = \text{Re} \left[\frac{\mu}{j\omega} \frac{\partial v_\theta}{\partial z} v_\theta^* \right] = \text{Re} \left[\frac{\mu}{j\omega} \frac{r^2}{R^2} \frac{\partial A(z)}{\partial z} A(z)^* \right]. \quad (3)$$

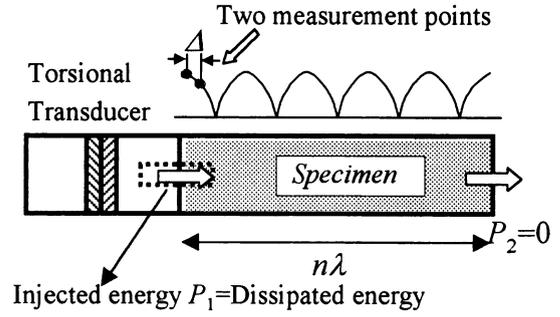


Fig. 2. Preparation of specimen: a bar of resonant length is excited by a Langevin transducer.

Here, μ and ω are the rigidity of the material and the angular frequency. An asterisk indicates the complex conjugate.

In our measurement, we use a straight bar of resonant length $L = n\lambda$ as a specimen, and drive with a Langevin torsional transducer at one end as shown in Fig. 2. λ is the wavelength of torsional vibration, and n is integer. In this case, since $P_2 = 0$ and all injected power P_1 is dissipated in the specimen, $W_d = 2\pi P_1 / \omega$. Integrating the flux given by Eq. (3) over the cross-section, the input effective power to the specimen P_1 is calculated as:

$$\begin{aligned} P_1 &= \int_0^{2\pi} \int_0^R I_z r dr d\theta \\ &= \text{Re} \left[\frac{\mu}{j\omega R^2} \int_0^{2\pi} \int_0^R \frac{\partial A(z)}{\partial z} A(z)^* r^3 dr d\theta \right]. \end{aligned} \quad (4)$$

In the practical measurement, the spatial derivative is represented by the finite difference of the vibration velocities between two points separated by a small distance of Δ :

$$\begin{aligned} \frac{\partial A(z)}{\partial z} A(z)^* &= \frac{V_2 - V_1}{\Delta} \frac{V_2^* + V_1^*}{2} \\ &= \frac{1}{2\Delta} [(A_2^2 - A_1^2) + 2jA_1 A_2 \sin(\phi_2 - \phi_1)]. \end{aligned} \quad (5)$$

Here, V_1 and V_2 are complex vibration velocities, whose amplitude and phase are A_1 , A_2 , ϕ_1 and ϕ_2 . We can use an approximation; $A_1 \approx A_2$, since $\Delta \ll \lambda$. We also assume a sinusoidal vibration distribution for the calculation of the kinetic energy W_k , since the vibration loss is small enough for high- Q materials. Then, the final representation of the Q -factor for the specimen in Fig. 2 is given by:

$$Q = \frac{2\pi^2 n}{\sin(\phi_2 - \phi_1)} \frac{\Delta}{\lambda}. \quad (6)$$

Here, we have used the relationship between the phase velocity of a torsional wave, the frequency and the

wavelength: $f^2\lambda^2 = \rho/\mu$. It should be noted again that the form of Eq. (6) contains approximations valid for high- Q materials, and Eqs. (1)–(5) should be used for evaluating low- Q materials such as polymers or plastics.

3. Error analysis

Eq. (6) shows that the Q -factor can be estimated by measuring the phase difference between two points with a small separation Δ . In the case of high- Q materials, the phase difference is small, and the resolution of the phase measurement determines the error in the Q -factor estimated by the present method. It is readily concluded from Eq. (6) that a resolution of 0.05° in the phase measurement is required for the estimation of the Q -factor with an error less than 10% for a specimen; $Q = 1000$, $n = 5$ and $\Delta/\lambda = 0.1$. It is also noted that the error will be reduced if the length of specimen n is longer, since the energy flow at the input of the specimen becomes so high that the phase difference can be measured more easily. An optimum value exists for the spacing Δ between the two measuring points. The error due to the finite difference approximation of the spatial derivative tends to zero as the spacing Δ approaches zero. However, a finite difference calculation with too small a Δ amplifies the noise contained in the measured data. In our case, the deviation of the estimated Q -factor was minimized for $\Delta/\lambda = 0.1$ with a resolution in phase measurement of 0.01° . The value Δ/λ should be chosen carefully to be suitable for the instrument used in the measurement.

4. Instrumentation for the phase measurement

According to the discussion above, accuracy in phase is essential for the vibration measurement, while precise amplitude is not necessarily important. Hence, we employed an optical fiber probe method [6]. As illustrated in Fig. 3, a pair of optical fibers is placed near the specimen surface. One fiber fed by a light source illuminates the surface, and the other fiber picks up a part of the reflected light. Half of the specimen surface is so painted that there is a step in optical reflectivity across the direction of vibration displacement. The received light intensity is modulated in proportional to the in-plane displacement due to the torsional vibration of the specimen. This method has no loading effect on the vibration. Above all, the response of the optical method is very fast and the phase delay is negligible in the frequency range used in our measurements, although the amplitude sensitivity is affected by the optical reflectivity. Phases at two points are measured simultaneously by two separate fiber probes to avoid

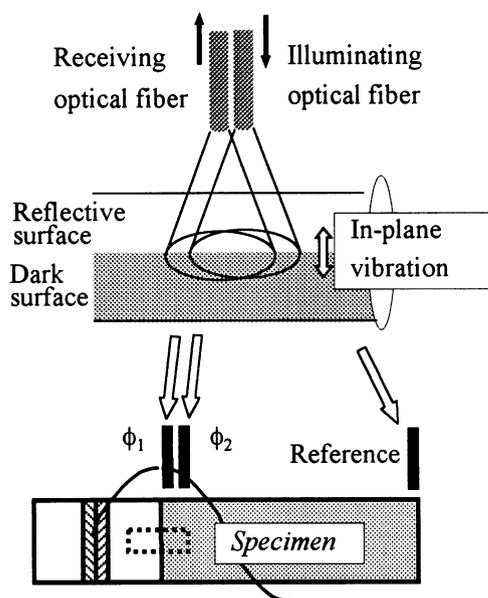


Fig. 3. Fiber probe for measuring in-plane displacement and the location of the probes.

the effect of temporal fluctuation of the vibration system. The phase was measured by a lock-in amplifier (NF-5560), whose phase resolution was 0.01° . The vibration at the end of specimen was monitored by another fiber probe to produce the reference signal for the lock-in detection.

5. Measured results

5.1. Measurement of the dissipated power

We measured the local dissipated power by the proposed technique to make a qualitative verification of estimating the loss from the power flow. An acrylic resin was chosen as a sample, since its temperature rise can be observed without difficulty owing to high loss and low heat transfer. It is expected that the loss generation and the resulting temperature rise will become large at the nodal position of the standing vibration. The torsional vibration was excited on the acrylic bar of resonant length by a Langevin torsional transducer. The sample was connected to the transducer with a bolt, and the frequency and the diameter of the sample were 25 kHz and 30 mm, respectively. Fig. 4 shows the vibration distribution along the sample bar. The magnitude of the vibration velocity and its phase were measured by an in-plane laser Doppler vibrometer. Acrylic resin is a highly lossy medium at ultrasonic frequency, and a large amount of the traveling wave component is observed together with the standing wave component. The local dissipated power at the position z is calculated as the spatial derivative of the power flow given by

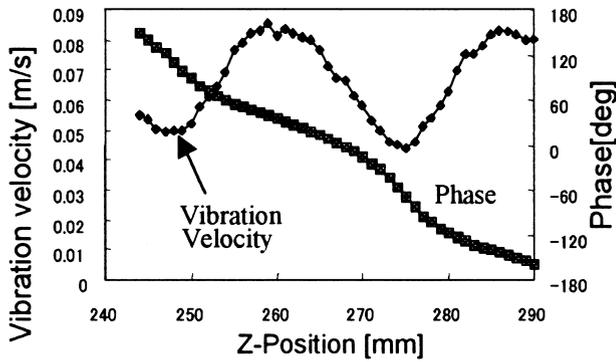


Fig. 4. Torsional vibration distribution along the axis of an acrylic resin bar.

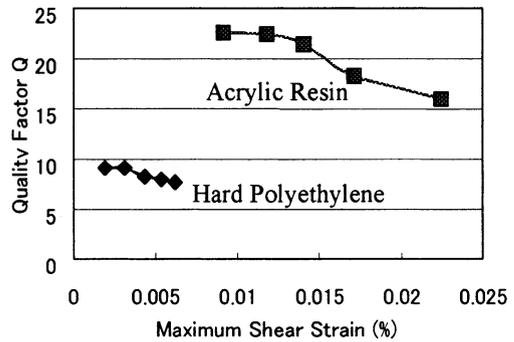


Fig. 7. Measured Q -factors for polymers.

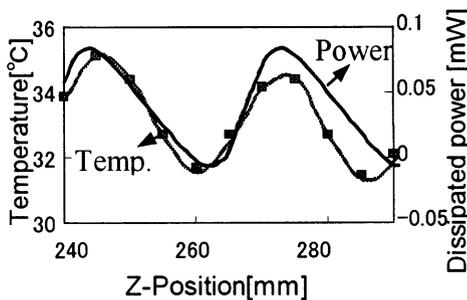


Fig. 5. The local dissipated power estimated from the vibration distribution by the proposed method and the temperature measured by a non-contact thermometer.

Eq. (4). The result is shown in Fig. 5. The temperature measured by an IR radiation thermometer is also plotted in Fig. 5. It is clearly observed that the loss is large at the vibration node as expected. Consequently, the dissipated power can be estimated from the energy flow as proposed in this paper.

5.2. Measurements of Q -factor

First, several kinds of metals were measured by the proposed method. The results for steel, stainless steel, titanium, duralumin, super duralumin and brass are summarized in Fig. 6. Q -factors are plotted as functions of the strain at the node of the specimen. The length and diameter of the specimen were five times the wave-

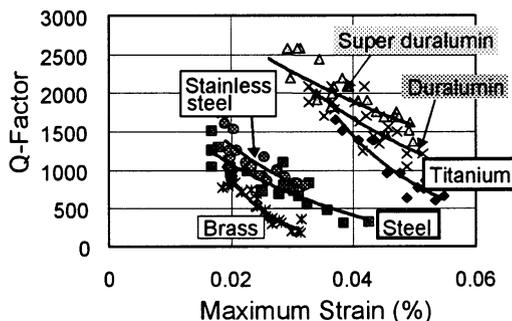


Fig. 6. Measured Q -factors for metals.

length and 30 mm, respectively. The specimens were driven by a torsional Langevin transducer at 30 kHz. The range of strain in this experiment corresponds to the vibration velocity of from 0.4 to 1.6 m s⁻¹ at the circumference of the specimen. The Q -factor decreased as the strain became high in all the materials. The Q -factor of brass is low and is reduced rapidly by the strain, while that of super duralumin is fairly high and maintains a high value at a high strain level. These results are with torsional vibration, and the absolute values of the Q -factors might be much lower than that for longitudinal vibration. Q -factors measured by the conventional method with electrical frequency response at low level excitation were 2300 for the stainless steel sample and 1100 for the duralumin sample, for example. These values are lower than the extrapolation of the data measured by the proposed method. This is because the electrical method gives the overall Q -factor of the vibration system with piezo-ceramics, metals and their joints, while the proposed method gives the Q -factor of the specified metal part.

In Fig. 7, the results for acrylic resin and hard polyethylene are presented to demonstrate the measurement for low- Q materials.

6. Conclusions

A method to measure the Q -factors of materials at high vibration was proposed for torsional vibration. On the basis of this method, Q -factors for several popular metals and polymers were measured with the use of an optical fiber technique. The dependence on vibration strain was presented in torsional vibration at 25 and 30 kHz. This method can be applied for other vibration modes such as longitudinal vibration and bending vibration, if appropriate modifications are made. Theoretical and experimental discussions on error in detail should be conducted for discriminating small difference in vibration properties between the same kind of materials with small differences in composition, doping and processing.

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