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Evaluation Method of Materials for Power Ultrasonic Applications

パワー超音波用材料の振動特性評価

Kentaro Nakamura† (Tokyo Inst. of Tech.)
中村健太郎† (東工大)

1. Introduction

Usages of ultrasonic tecnologies are devided into two categories: sensing and power applications. In the case of power applications, which spread in wide area such as cleaning, mechanical processes, chemical reactions, and actuators, components for vibration system including piezoelectric element and other vibration materials need to be carefully chosen being based on their mechanical loss under high vibration strain. In this paper, several basic knowledges on how to evaluate the high vibration characteristics of materials will be introduced. First, a transient method is explained for evaluating piezoelectric ceramics, and some of practical data are exhibited. Second, a method to measure the quality factor (Q-factor) of non-piezoelectric materials is explained being based on the definition of Q-factor and structual intensity theory.

2. Transient Method for Measuring Q-factor of Piezoelectric Element at High Vibration Amplitude

A rectangular piezoelectric plate sample is prepared as shown in **Fig. 1** for measureng the high amplitude characteristics. It is driven at around the fundamental longitudinal resonance frequency f_0, where the longest length L is equal to the half wavelength of the longitudinal wave.

$$f_0 = \frac{1}{2L}\sqrt{\frac{E}{\rho}} \tag{1}$$

Here, ρ is the density, and E is the Young's modulus in the length direction of the element for the short-circuited condition. Commonly, Q-factor is measured at low vibration amplitude from the resonanace courve under continuous excitation as

$$Q \approx \frac{f_0}{f_2 - f_1}, \tag{2}$$

referring **Fig. 2**. However, at high level of vibration stress, the resonance frequency is lowered due to the softning effect, and it is difficult to obtain the resonance curve stably. This is a typical non-linear phenomenon in piezoelectric ceramic materials.

Instead of the continuous excitation, a transient method has been proposed by Umeda et al [1, 2], which is adapted as ISO21819 [3]. The sample element is excited in the vicinity of the resonanace frequency with sufficiently high vibration amplitude. The electrical driving source is cut off at t=0, and the electrical terminal of the element is short-circuited. This is simply done by turnig the output voltage of the oscillator to zero if a power amplifier with almost zero output impedance is used.

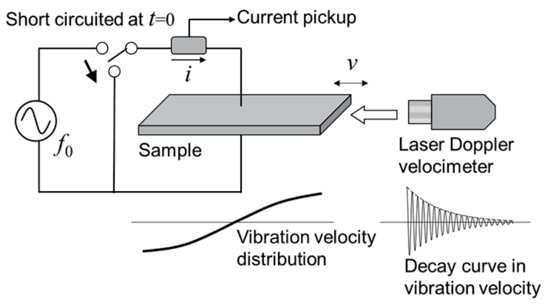

Fig. 1 Setup for transient measurement.

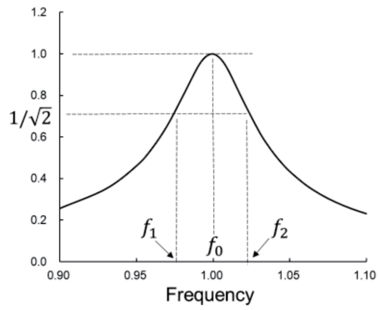

Fig. 2 Resonance curve.

The vibration velocity at the end of the element is measured using a laser Doppler velocimeter (LDV). We can record an exponential decay in the vibration velocity as well as in the short-circuited current after the driving voltage becomes zero. If the Q-factor is constant for different vibration amplitude, the envelope of the decay in vibration velocity is $e^{-t/\tau}$, where the time constant τ is given by the Q-factor and the resonance frequency f_0 as

$$\tau = \frac{Q}{\pi f_0}. \tag{3}$$

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In practical piezoelectric elements, the time constant in the decay curve varies as the time since the Q-factor changes according to the vibration stress. Q-factors were measured and plotted as functions of the vibration velocity in **Fig. 3** for several different piezoelectric ceramics. It is obvious that the Q-factor drops rapidly as the vibration velocity exceeds 0.5 m/s, which roughly corresponds to the stress of 15-20 MPa. The results in Fig. 3 are free from the temperature effects since the measurement is completed in very short time.

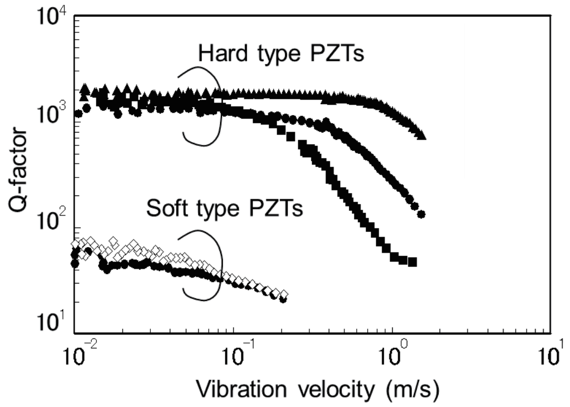

Fig. 3 Q-factors as functions of vibration velocity.

3. Q-factor of Non-Piezoelectric Material

To evaluate Q-factors of non-piezoelectric materials, a method based on the original definition of Q-factor [4, 5]:

$$Q = 2\pi \times \frac{\text{Stored reactive energy}}{\text{Dissipated energy for a period}} = \frac{2\pi W_k}{W_d} \quad (4)$$

A sample bar to be evaluated is connected to a bolt-clamped Langevin transducer as illustrated in **Fig. 4**. The length of the sample is set to the multiple of the half-wavelength to resonate at the driving frequency. Though a standing wave is excited along the sample, a slight attenuation exists due to the loss generated in the sample, which results in the limited Q-factor. The Q-factor is calculated for a small slice in the sample bar being based on eq. (4). The kinetic energy is calculated from the measured average vibration velocity at the slice for the stored reactive energy in eq. (4). The energy dissipated in the slice is the difference between the incoming active energy across the left boundary L1 of the slice and the outgoing active energy across the right boundary L2. The active energy flow at the boundary is calculated being based on the theory of structural intensity [6]. Structural intensity is the Poynting vector for elastic vibration in solid, which is calculated with the stress tensor $\boldsymbol{T}$ and the vibration velocity vector $\boldsymbol{v}$ as

$$P = \int_S \boldsymbol{T} \cdot \boldsymbol{v}^* dS \quad (5)$$

To know the active component, time-average need to be taken. In Eq. (5), time-average is calculated through the nature of complex number. The practical form for the calculation depends on the vibration category: longitudinal, torsional and flexural vibrations. Examples of Q-factors of typical metals are summarized in Fig. 5.

4. Summary

Methods to evaluate Q-factors of piezoelectric and non-piezoelectric materials for high power applications of ultrasonic vibrations were described.

References

1. M. Umeda, K. Nakmaura, S. Ueha, *Jpn. J. Appl. Phys.*, **37**, Part 1, 9B, 5322-5325, 1998.
2. M. Umeda, K. Nakmaura, S. Ueha, *Jpn. J. Appl. Phys.*, **38**, Part 1, 9B, 5581-5585, 1999.
3. https://www.iso.org/standard/71874.html
4. K. Nakamura et al., *Ultrasonics*, **38**, 122-126, 2000.
5. J. Wu, Y. Mizuno, K. Nakamura, *Ultrasonics*, **91**, 52-61, 2019.
6. G. Pavic, *J. Sound and Vib.*, **49**, Issue 2, 221-230, 1976.

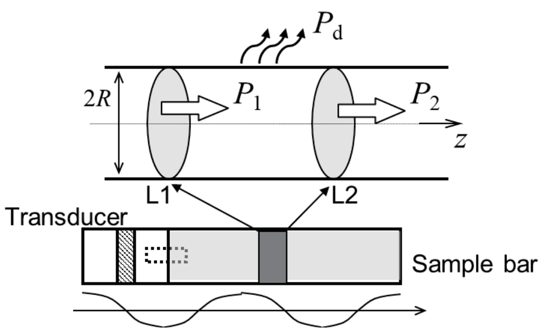

Fig. 4 Method to evaluate Q-factor of non-piezoelectric material.

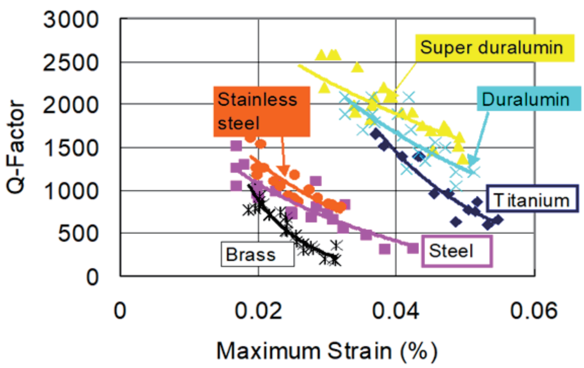

Fig. 5 Q-factors in torsional vibration for typical metals measured at 30 kHz.