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High Power Characterization of Piezoelectric Materials

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Abstract. Three techniques for measuring high voltage/power piezoelectric properties, which have been developed recently, are compared: a voltage-constant piezoelectric resonance method, a current-constant piezoelectric resonance method, and a pulse drive method. The conventional resonance method with a constant voltage circuit exhibits significant distortion (or a hysteresis) in the resonance frequency spectrum under a high vibration level due to large elastic non-linearity, which limits precise determination of the electromechanical coupling parameters. To the contrary, the resonance method with a constant current circuit (i.e., constant velocity) can determine the coupling parameters more precisely from a perfectly-symmetrical resonance spectrum. The general problem in both resonance methods is heat generation in the sample during the measurement. In order to separate the temperature characteristic from the non-linearity, it is recommended that the pulse method be used in parallel, even though the accuracy is not very high.

Keywords: high power, piezoelectric, resonance/antiresonance, pulse drive method

Introduction

High voltage/power piezoelectric devices such as piezoelectric actuators, ultrasonic motors and piezoelectric transformers have been developed intensively in recent years [1–3]. Here, the piezoelectric actuators are driven under a comparatively high applied voltage, in order to obtain high deformation and/or force. The electromechanical coupling data that the manufacturers provide are usually determined under a low applied voltage (1 V) with an impedance analyzer, and often disagree with the high voltage experiments. Figure 1 illustrates the change in mechanical quality factor Q with increasing vibration velocity for $Pb(Zr,Ti)O_3$ based ceramics (doped with 2.1at.% of Fe). In this paper, the vibration velocity which is a parameter for indicating the vibration level and is independent of the sample size, is used preferably to the applied ac electric field or voltage. The reason is that the applied field does not provide a proportional relation with the vibration amplitude: a large portion of the input electric energy is dissipated through heat generation [4]. The mechanical quality factor Q decreases drastically, by 80%, on increasing vibration velocity from 0.05 m/s to 0.5 m/s [5]. The morphotropic phase boundary composition with the

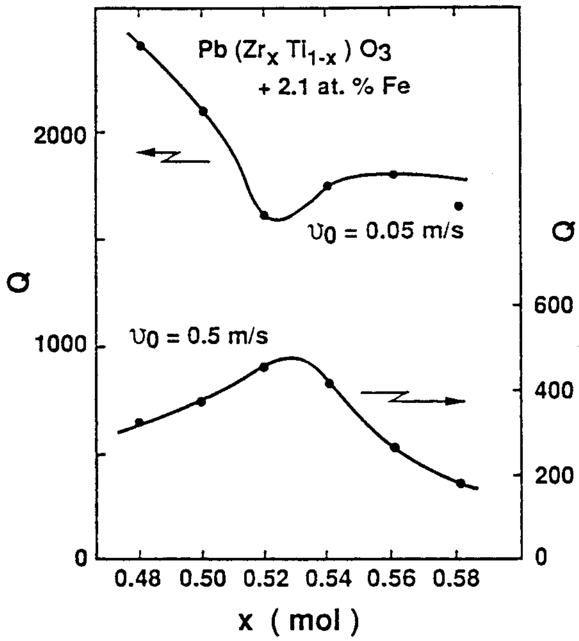


Fig. 1. Mechanical Q versus basic composition x at effective vibration velocity $v_0 = 0.05$ m/s and 0.5 m/s for Pb(Zr_xTi_{1-x})O_3 + 2.1at.% Fe ceramics.

lowest Q value at a small vibration velocity (this is a well-known fact!) exhibits the highest Q value at a high vibration velocity. Thus, low-vibration velocity measurements are not useful to evaluate the high-vibration velocity values, and high power electromechanical coupling parameters must be measured under a large vibration level.

In this paper we will compare three new techniques for measuring high-voltage piezoelectric constants which we have developed recently: a voltage-constant piezoelectric resonance method, a current-constant piezoelectric resonance method, and a pulse drive method. The resonance methods, in general, generate heat in the sample during the measurement, while the pulse method is not associated with temperature rise.

To the authors' knowledge, few papers have been published on the high voltage/power characteristics of piezoelectric materials to date. Thus, the literature cited is largely from our group's work.

Resonance/Antiresonance Methods

Piezoelectric transducers have two characteristic electromechanical resonance modes: resonance and antiresonance from an electrical point of view. It is well known that the mechanical vibration level of the piezoelectric sample is enhanced at the resonance frequency when driven under a constant voltage. It is worth noting that the piezoelectric transducer can also provide large vibration levels even at the antiresonance frequency when driven appropriately. For this reason, the resonance and antiresonance are sometimes designated A-type and B-type resonances from a mechanical viewpoint [4].

1. Constant Voltage Method

The conventional measurement method is the constant voltage type, which includes impedance analyzers. Figure 2 shows a fundamental circuit for measuring the piezoelectric resonance. L_m, C_m, R_m and C_d are the equivalent motional inductance, capacitance, resistance and damped capacitance of the admittance-type equivalent electric circuit for a piezoelectric resonator. The measurement was done using a frequency response analyzer (NF Corporation, 5090) coupled with a high power amplifier (NF Corporation, 4005). A constant voltage measurement provides an admittance curve as a function of frequency, as shown in Fig. 3. From the resonance (maximum) and the antiresonance (minimum) frequencies, the electromechanical coupling parameters are determined [6]. For a rectangular piezo-ceramic plate, for example, the k_{31} value can be calculated as

$$k_{31}^2/(1-k_{31}^2) = (\pi^2/4)(\Delta f/f_r). \qquad (\Delta f = f_a - f_r) \quad (1)$$

However, with increasing vibration velocity, the resonance spectrum distorts significantly, sometimes exhibiting large hysteresis or a jump of the peak curve upon rising and falling drive frequency. Figure 4

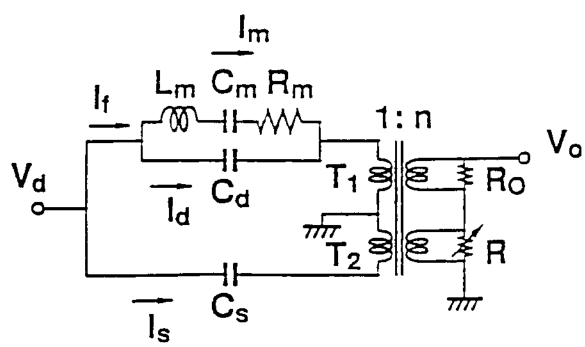


Fig. 2. Conventional constant voltage measurement circuit.

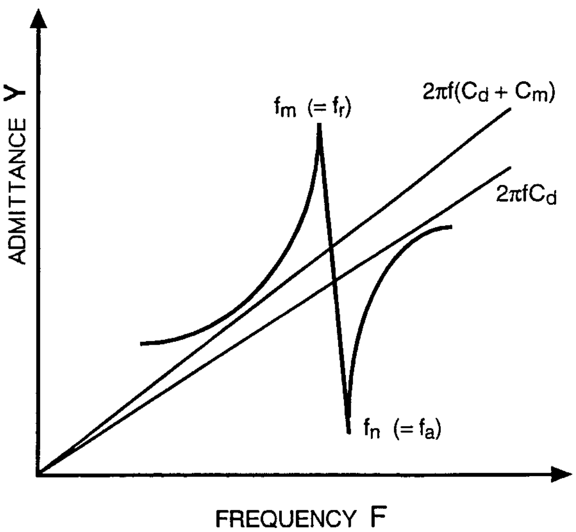


Fig. 3. Admittance curve as a function of frequency measured around the resonance and antiresonance modes under a constant voltage condition.

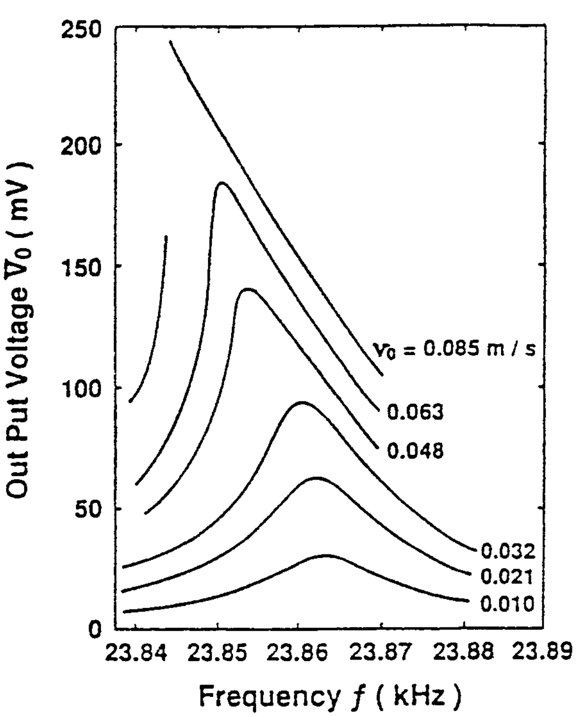


Fig. 4. Resonance curves for various vibration velocity measured by the constant voltage method for a PZT based ceramic. The output voltage V_0 is proportional to the current and the admittance. The inserted v_0 is an effective vibration velocity.

shows sample data measured for a PZT based ceramic (NEPEC-6) plate, where the output voltage V_0 is proportional to the current or the admittance [7]. This spectrum distortion causes a serious problem in determining the electromechanical coupling parameters precisely. The distortion originates in elastic nonlinearity, because a very large mechanical vibration is excited at the resonance when a constant voltage method is employed. Figure 5 shows a rough estimation (by neglecting the spectrum distortion) of the ac voltage dependence of the electromechanical parameters keeping the dc bias at 35 V [8]. Here, the samples were PLZT based disks, 10 mm in diameter and 0.7 mm in thickness, and H and S in the figure denote hard and soft type piezoelectrics, respectively. Notice a large decrease in the resonance frequency and insensitive behavior in the antiresonance frequency with increasing ac drive voltage, leading to an apparently large increase in the electromechanical parameter k_p. It is important, however, to note that some portion of this large change is attributed to the temperature rise.

2. *Constant Current Method*

Around the electromechanical resonance frequency, the vibration amplitude of a piezoelectric transducer is not proportional to the voltage, but to the current, as shown in Fig. 6 [9]. Therefore, to determine the electromechanical coupling parameters precisely, an admittance curve should be taken under a constant current condition, i.e., under a constant vibration amplitude [10]. Figure 7 introduces an automatic measurement circuit with a differential circuit to maintain a motional current constant. Keeping the current constant, the impedance curve can be obtained as a drive voltage (V_d) minimum around the resonance frequency. As demonstrated in Fig. 8, a constant current measurement provides a completely symmetrical impedance peak spectrum without a hysteresis or a jump phenomenon up to a high vibration velocity level [7]. Using a profile fitting technique to the resonance spectrum, we can determine the necessary components, i.e., inductance, capacitance, resistance of the admittance-type equivalent electric circuit for a piezoelectric resonator. On the other hand, to determine the electromechanical coupling parameters at the antiresonance, a constant voltage condition (i.e., the conventional method) should be employed, because the admittance of the resonator is very small.

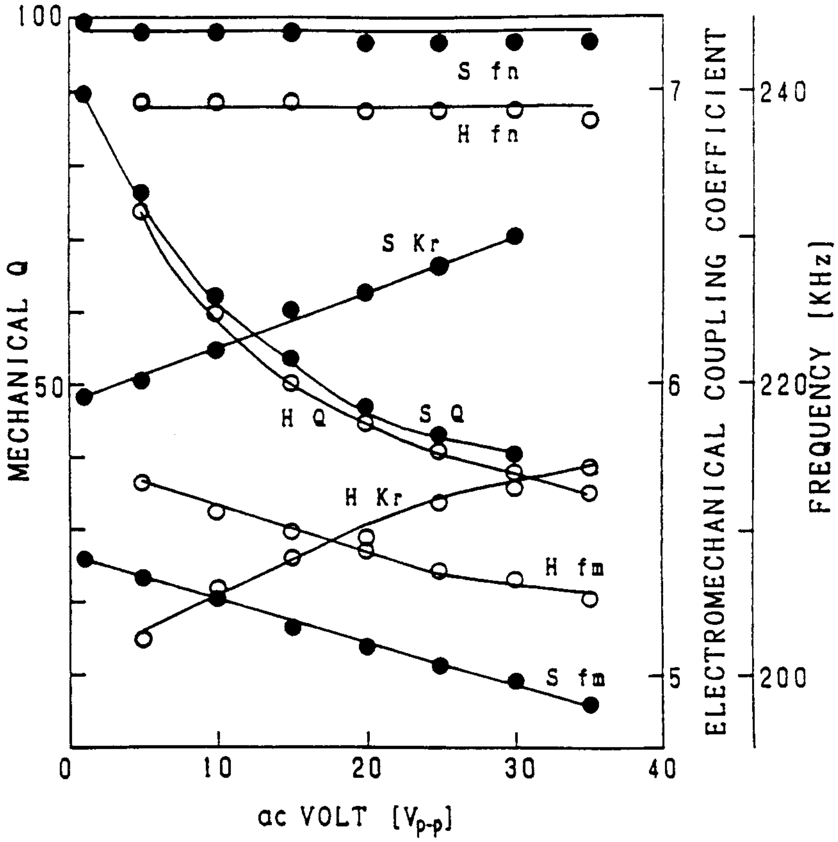


Fig. 5. The ac voltage dependence of the electromechanical parameters for a fixed dc bias of 35 V measured for PZT based ceramic disk samples. H and S denote hard and soft piezoelectrics, respectively.

Figure 9 illustrates mechanical quality factors, Q_A, Q_B, for A-type (resonance) and B-type (antiresonance) resonance modes, and the temperature rise for the both modes for a rectangular-shape hard PZT resonator plotted as a function of vibration velocity [10]. The sample size is indicated in the figure (43 mm × 7 mm × 2 mm). Note again that an ''effective'' vibration velocity v_0 is a material's constant independent of the sample size, and was defined as $\sqrt{2}\cdot\pi f\cdot u_m$, where f is the resonance or antiresonance frequency and u_m is the maximum vibration amplitude of the piezoelectric device. The vibration amplitude was monitored with a photonic sensor simultaneously during the impedance measurment. It is important to note that the mechanical quality factor decreases drastically above a certain critical vibration velocity (0.1 m/s), where a steep temperature rise starts. We have suggested that the heat generation is mainly attributed to a $P-E$ hysteresis loss rather than the mechanical loss [11,12]. Note also that Q_B is higher than Q_A over the entire vibration velocity range, and that the temperature rise of the sample is less for the B-type resonance (antiresonance) than for the A-type resonance for the same vibration level. This indicates an intriguing idea that the antiresonance mode should be superior to the conventional resonance mode, particularly for high power applications such as ultrasonic motors.

Pulse Drive Method

An alternative method for measuring high voltage piezoelectric characteristics is the pulse drive method. By applying a step electric field to a piezoelectric sample, the transient vibration corresponding to the desired mode (extentional, bending etc.) is measured. This real time monitoring of the transient vibration

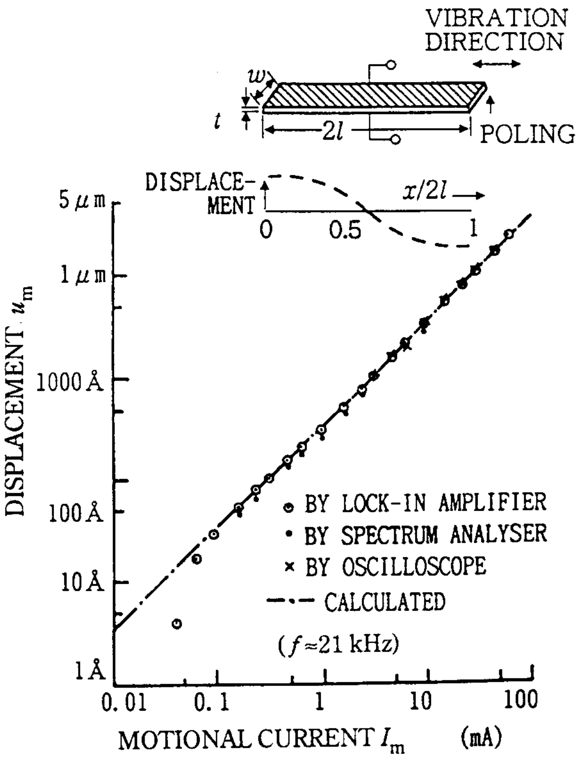


Fig. 6. Displacement versus motional current of a PZT rectangular plate at the resonance frequency.

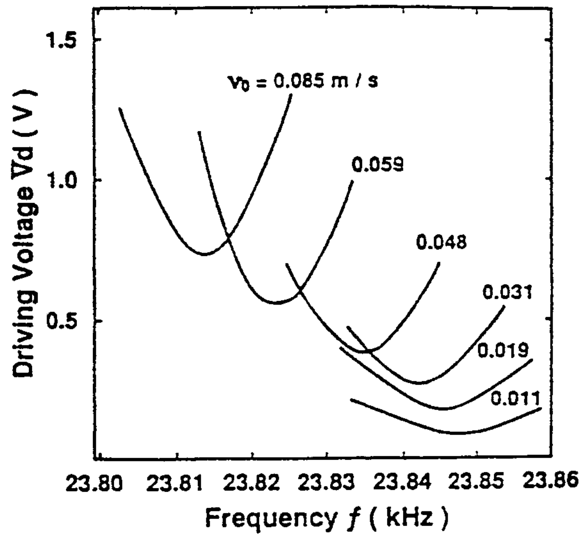


Fig. 8. Resonance curves measured by the constant current method for a PZT based sample.

should be mathematically equivalent to the above-mentioned frequency domain measurement using a resonance/antiresonance technique through the Fourier transformation. Figure 10 shows a typical measurement for a multimorph PZT based actuator whose structure is illustrated in Fig. 11(b). The resonance period, saturated displacement and damping constant are obtained experimentally, from which the elastic compliance, piezoelectric constant, mechanical quality factor and electromechanical coupling factor can be calculated.

An example procedure to determine the electro-

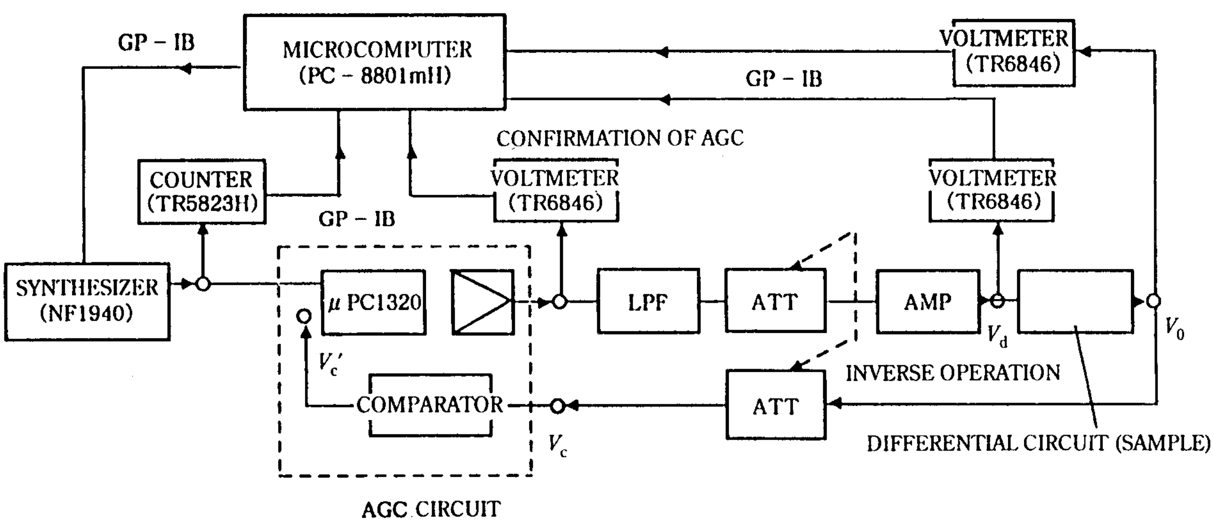


Fig. 7. Automatic measurement system with constant driving current.

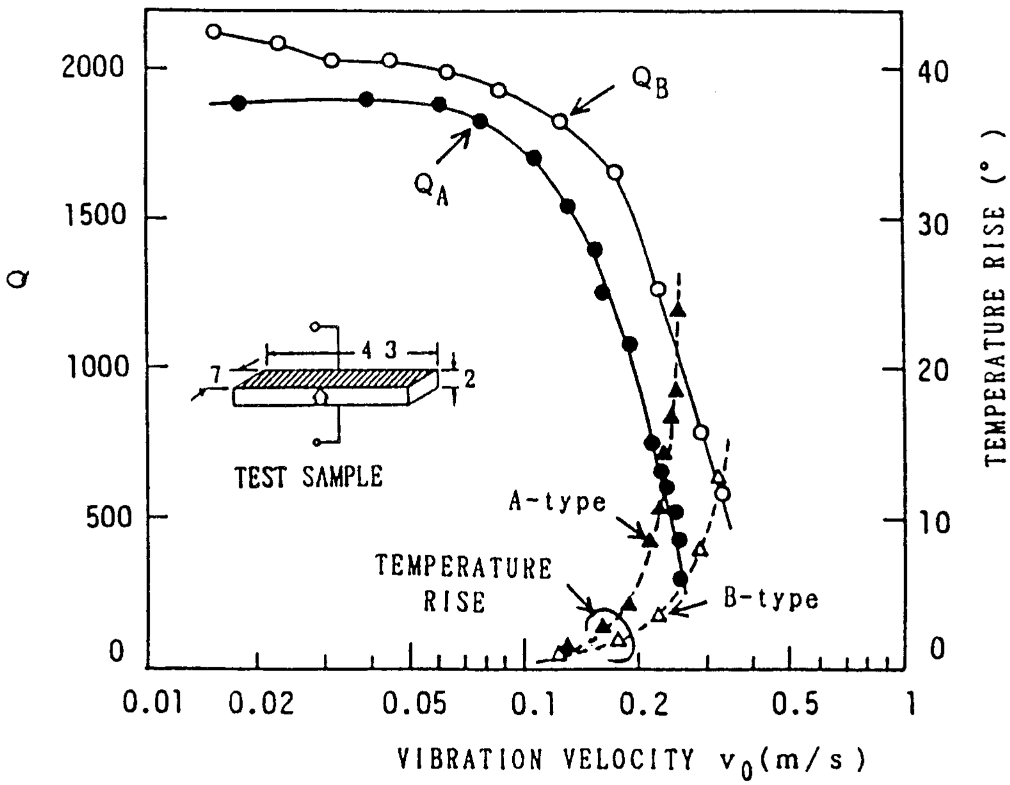


Fig. 9. Vibration velocity dependence of the quality factor and the temperature rise for both A- (resonance) and B- (antiresonance) type resonances of a rectangular PZT resonator. The sizes in mm are inserted.

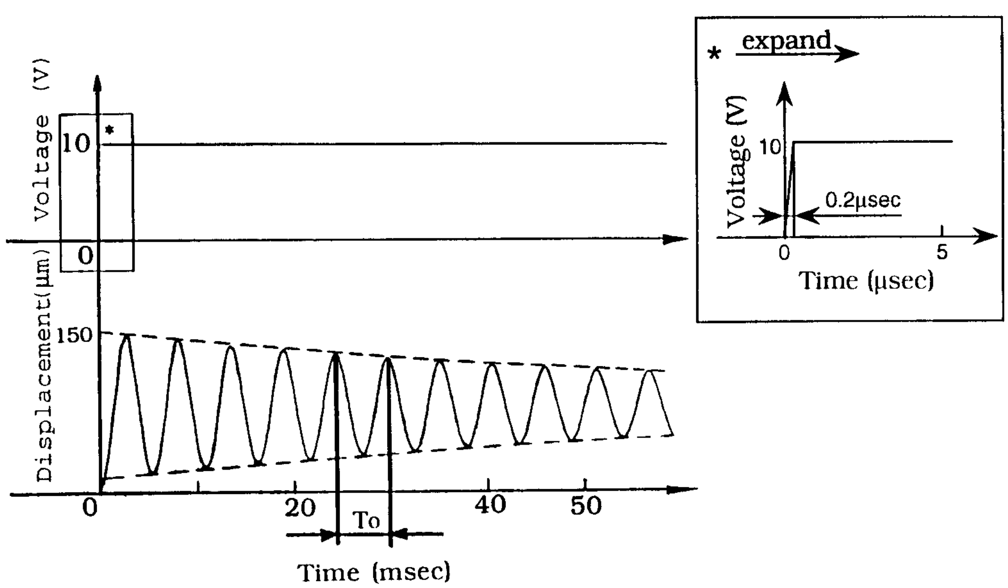


Fig. 10. Pulse drive technique for measuring the electromechanical parameters.

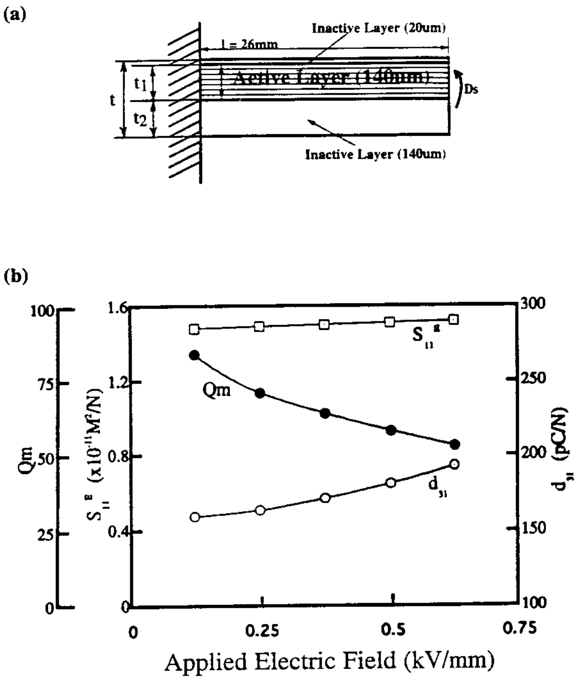


Fig. 11. Applied electric field dependence of the electromechanical parameters in a multimorph PZT piezoelectric actuator measured by the pulse drive method.

mechanical parameters is described for a multilayer piezo-actuator. Knowing the permittivity ε, density ρ and size (length) L of the sample, independent of the pulse drive experiment, the piezoelectric constant d_{33} can be determined at first from the stabilized displacement D_s after applying a step voltage:

$$D_s = d_{33}E_3L \tag{2}$$

Second, from the resonance period T_0 or the resonance frequency f_r $(=1/T_0)$ which can be obtained from the ringing period, elastic compliance s_{33}^E can be calculated:

$$f_r = 1/2L(\rho s_{33}^E)^{1/2} \tag{3}$$

Then, the electromechanical coupling factor k_{33} is obtained from

$$k_{33} = d_{33}/(\varepsilon_{33}^X s_{33}^E)^{1/2} \tag{4}$$

Finally, the mechanical quality factor Q_m is calculated from the damping constant τ:

$$Q_m = (1/2)\omega_0\tau. \quad (\omega_0 = 2\pi/T_0) \tag{5}$$

Although the experimental accuracy is not high, the simple setup is attractive especially due to its low cost. Moreover, unlike the resonance/antiresonance methods, this technique requires only one voltage pulse, and thus does not generate heat. The detailed theoretical background of this technique was described in our previous textbook [4].

Figure 11 shows the applied field dependence of the electromechanical parameters in the PZT based multimorph actuator, the structure of which is also inserted in the figure. A significant increase with increasing the electric field was found in the piezoelectric constant d_{31} and electromechanical coupling factor k_{31}, while a decrease was observed in the quality factor Q_m.

Finally, high power characteristics of soft piezoelectric PZT-based ceramic samples measured by the constant current and pulse drive methods are compared in Fig. 12. Here, an equivalent vibration velocity for the pulse drive method was estimated by

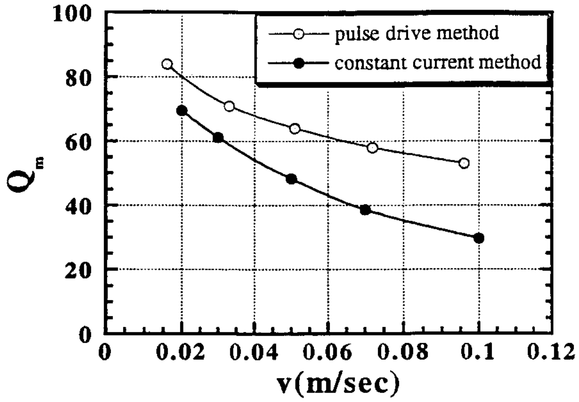
$$v = (u_{p-p}/2\sqrt{2})(2\pi f_r) \tag{6}$$

where u_{p-p} is twice the maximum vibration amplitude of ringing. Although the absolute values were different due to slightly different compositions of the two samples, similar tendency with changing vibration velocity, i.e., a drastic decrease in Q_m and an insensitive change in the elastic compliance $s_{11}{}^E$, was obtained for both the measuring methods. A demonstration using exactly the same sample is in process.

Conclusions

This paper demonstrated significant changes in electromechanical parameters such as piezoelectric constants and mechanical quality factors with increasing applied electric field or vibration velocity, thus concluding that high power electromechanical coupling parameters must be measured under a large vibration level.

Comparisons among new three techniques for measuring high voltage/power piezoelectric properties were made: a voltage-constant piezoelectric resonance method, a current-constant piezoelectric resonance method and a pulse drive method. The resonance methods, in general, generate heat in the sample during the measurement, while the pulse method is not associated with temperature rise. The conventional resonance method with a constant voltage circuit reveals a significant distortion (or a



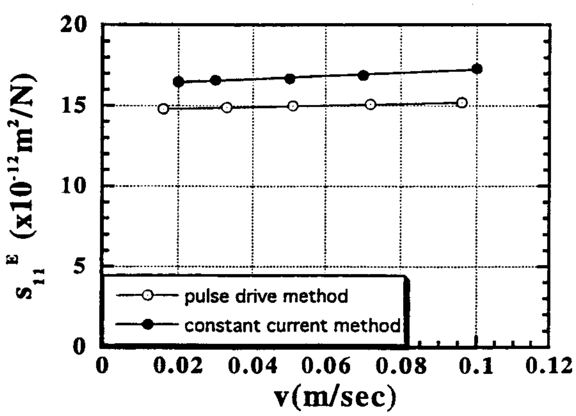


Fig. 12. Comparison of high power characteristics in soft piezoelectric PZT-based ceramic samples measured by the constant current and pulse drive methods. Note that the two samples have slightly different compositions.

hysteresis) of the resonance frequency spectrum under a high vibration level, which prohibits precise determination of the electromechanical coupling parameters. To the contrary, the resonance method with a constant current circuit can determine the coupling parameters precisely from a perfectly-symmetrical resonance spectrum.

Merits (+) and demerits (−) of these measurement techniques for high power piezoelectic characteristics are summarized:

(1) Resonance/antiresonance method — − Heat generation
- a) Constant voltage method — − Distortion of the resonance spectrum; − Vibration velocity change
- b) Constant current method — + Symmetric resonance spectrum; + Constant vibration velocity measurement

(2) Pulse drive method — + No heat generation; − Low accuracy

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