

Relativity of Electric Field to Resonance Characteristics and Piezoelectric Constants of Modified PZT Ceramics

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The practical applications of piezoelectric ceramics are applied not only under low electric field environment. Therefore, an examination for characteristics of PZT ceramics under the high electric field condition can contribute to reducing the susceptibility of multifarious applications and to facilitating production of control circuits. These contributions can lead to the expansion of industrial applications. In this research, we fabricated disk-type PZT ceramic samples using conventional methods, measured the resonance characteristics of these samples under from low to high voltage conditions and calculated the PZT constants. [DOI: 10.4313/TEEM.2009.10.6.196]

Keywords: Electric field dependence, Non-linear characteristics, Material property, Modified PZT

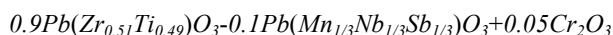
1. INTRODUCTION

Since piezoelectric phenomenon able to develop an electric charge proportional to a mechanical stress discovered by J. and P. Curie first, this material has been utilized as core material in diversity fields [1]. Generally, material properties of PZT ceramics are measured under the small signal input. Concrete concept and process are stated clearly in the international standards [2]. The various material constants, determined by these methods are accepted as being trustworthy. In high power devices, such as ultrasonic motors and PZT actuators need a high level or great vibration amplitude, large input signals should be provided to the PZT elements. In accordance with many previous researches, material properties of PZT ceramics shows the linear characteristics only limited ranges of input voltages [3-5]. Hence, it is difficult to estimate the suitability of PZT ceramic material in case of high power applications. In Institute of Radio Engineers (IRE) standards, the material properties are able to be acquired from frequency-impedance characteristics of PZT ceramics [2]. Therefore, if these relations are varied with the applied input voltage, the material constants, calculated by the method enshrined in the standards, undergo changes necessarily. This fact signifies that the material properties of PZT ceramics are affected by the applied electric fields. In this study, we fabricated the disk type PZT ceramic specimens by conventional methods and considered the electric field dependence of frequency-impedance characteristics. And also, we calculated the PZT constant d_{33} using the resonance method of the IRE standards from those frequencies representatively.

2. EXPERIMENTS

2.1 Specimen fabrication

We used PZT - PMNS ceramics as disk type specimens in this experiment. PZT-PMNS ceramics definite composition is shown as follows [6].



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To increase the dielectric and PZT properties of PZT ceramics significantly, MnO_2 , Nb_2O_5 , Sb_2O_3 were added. Mixing ratio was determined by considering morphotropic phase boundary of ceramics. Cr_2O_3 was added to improve the mechanical quality factor (Q_m) and to reduce the dielectric loss ($\tan \delta$). This material shows excellent properties of high mechanical quality factor, high electro-mechanical coupling factor (k_p) and low dielectric loss. The disk type ceramic specimens based on this material were fabricated. It had 28-mm diameter and 1-mm thickness.

2.2 Measurement process

The system for measuring resonance characteristics according to input voltage is presented in Fig. 1. Output signal of the built-in oscillator in the frequency response analyzer(FRA 5087; NF Corporation, Japan) was amplified by a power amplifier to drive the PZT specimen. The voltage was applied to the specimen and measured from Ch1 of FRA. The current flowing through the specimen was converted into voltage multiplied by the shunt resistor and was inputted through Ch2. By setting the analysis mode of the frequency response analyzer to Ch1 / Ch2, the impedance of the PZT specimen was measured. By measuring impedance by sweeping the frequency of the internal oscillator, the frequency characteristics of impedance were obtained. Resonance characteristics of the specimen of PZT ceramics are measured under the input voltage from 1 V_{rms} to 25 V_{rms}.

2.3 Calculation process of PZT constants d_{33}

In order to analyze the variation of a PZT constant d_{33} due to the change of the electric field, we calculated by means of the resonance method of the IRE standards. In accordance with the IRE standards, the value of d_{33} can be reckoned by the following procedure step by step [2].

$$k_{33} = \frac{\pi}{2} \frac{f_r}{f_a} \tan\left(\frac{\pi}{2} \cdot \frac{f_a - f_r}{f_a}\right) \quad (1)$$

$$\frac{1}{s_{33}^D} = 4\rho f_a^2 k_{33}^2 \quad (2)$$

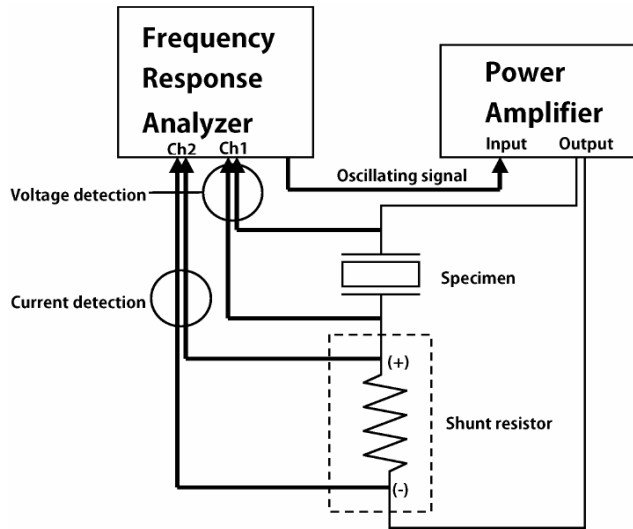


Fig. 1. Resonance characteristics measurement system.

$$s_{33}^E = s_{33}^D / (1 - k_{33}^2) \quad (3)$$

$$d_{33} = k_{33} \sqrt{\epsilon_{33}^T s_{33}^E} \quad (4)$$

The electro-mechanical coupling factor k_{33} is determined from the fundamental frequency f_a and f_r of thin cylinders. f_a and f_r mean the anti resonance frequency and resonance frequency respectively. s_{33}^D is acquired by sample size, density and anti resonance frequency.

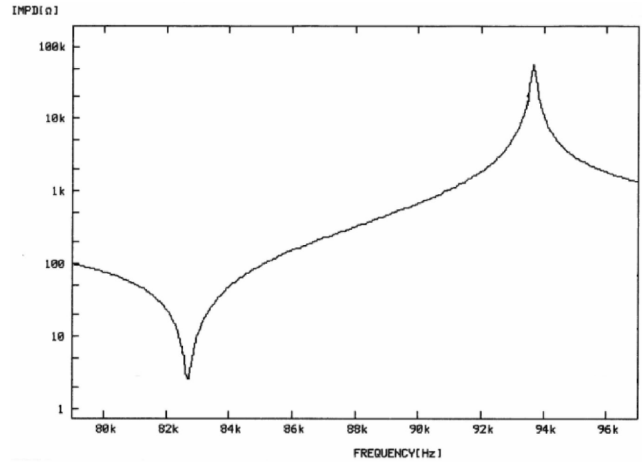
3. RESULTS AND DISCUSSION

3.1 Frequency-impedance characteristics

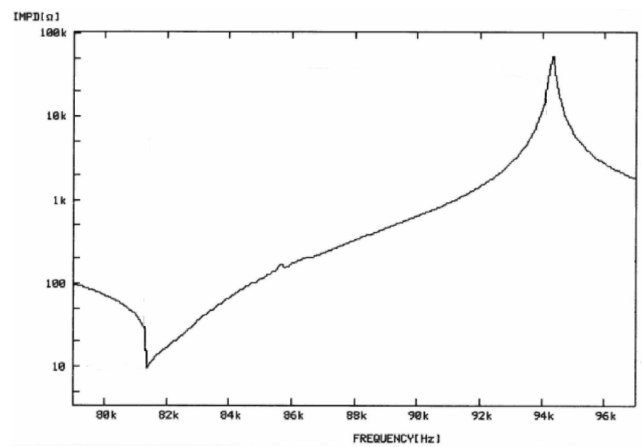
Impedance curves due to the magnitude of the input voltages are shown in Fig. 2. And the resonance and anti-resonance frequencies in accordance with the voltage variation are shown in Table 1. Input voltage was from 1 V_{rms} to 25 V_{rms} . In the first resonance mode of the specimen, the impedance according to the frequency was measured. When input voltages of 1 V_{rms} and 5 V_{rms} were applied, the impedance curve at the resonance and anti-resonance point had a bisymmetric shape and the value of impedance showed relatively large changes. But, when the input voltage was more than 10 V_{rms} , the impedance curve at the resonance point showed an asymmetric shape. Also, changes of the impedance value were relatively small. And this value varied steeply near the resonance frequency. Uchino *et al.* [7], explained that this phenomenon happened due to the non-linearity of the PZT characteristics using an electrical equivalent circuit. It seems that the variation of the frequency hardly harmonized with the mechanical vibration as the higher voltage was applied. As a result, the vibration change of dipoles which existed in the ceramic material seems to become sluggish.

Table 1. Resonance and anti-resonance frequencies in accordance with the voltage variation.

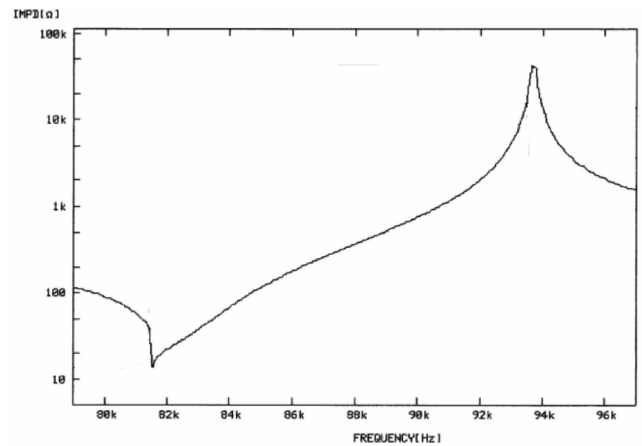
	1 V_{rms}	5 V_{rms}	10 V_{rms}	15 V_{rms}	20 V_{rms}	25 V_{rms}
f_r kHz	83.024	82.976	81.683	81.491	81.149	80.761
f_a kHz	94.135	94.151	94.223	94.114	93.754	93.501



(a) 1 V_{rms}



(b) 10 V_{rms}



(c) 20 V_{rms}

Fig. 2. Impedance characteristics variation according to input voltage.

Table 2. Calculation values of k_p and Q_m of specimen.

	1 V_{rms}	5 V_{rms}	10 V_{rms}	15 V_{rms}	20 V_{rms}	25 V_{rms}
k_p	0.4190	0.4201	0.4432	0.4447	0.4453	0.4480
Q_m	158.72	157.80	140.63	139.70	139.79	138.42

In IRE standards, the k_p is obtained from the fundamental mode f_r and f_a of a thin disk as follows.

$$k_p^2 = \frac{1}{p} \frac{f_a^2 - f_r^2}{f_a^2} \tag{5}$$

$$p = \frac{2(1 + \sigma^E)}{\eta_1^2 - 1 - (\sigma^E)^2} \tag{6}$$

σ^E is Poisson's ratio, and η_1 is the lowest positive root of $(1 + \sigma^E)J_1(\eta) = \eta J_0(\eta)$. J_0 is Bessel function of first kind and zero order, J_1 is Bessel function of first kind and first order [2].

The mechanical quality factor Q_m is obtained from the determination of the minimum impedance Z_r at the fundamental resonance. This measurement is accomplished by substitution of a variable resistance for the test specimen at f_r . Q_m is given by the follow relation.

$$\frac{1}{Q_m} = 2\pi f_r Z_r C^F \frac{f_a^2 - f_r^2}{f_a^2} \approx 4\pi Z_r C^F (f_a - f_r) \tag{7}$$

C^F is the capacitance measured under the low frequency condition (1 kHz). Table 2 shows the calculation results of k_p and Q_m by the upper equations. In accordance with the input voltage variation, the electromechanical coupling coefficient k_p is increased, but Q_m is decreased slightly.

3.2 Electric field - resonance frequencies variation

Figure 3 represents the variation of resonance frequency, anti-resonance frequency and the voltage reduction ratio at the resonance frequency, respectively. Specimen in Fig. 3 is 28 mm diameter and 1-mm thickness. When the electric field increased, the resonance frequency and the voltage reduction ratio decreased. The resonance characteristics were very similar tendencies as shown in the graphs. Peculiarity of these graphs was that the resonance frequency and voltage reduction ratio decrease steeply at a specific electric field, 5-10 V_{rms}/mm in Fig. 3. In case of the resonance frequencies in Fig. 3(a), the measured value at a 1 V_{rms}/mm was 83.0 kHz. The measured value at 25 V_{rms}/mm was 80.8 kHz. Shift of the resonance frequency was about 2.2 kHz. As the electric field increased, the decrement of the resonance frequency was found. Therefore, the resonance frequency shift may have considerably occurred in the case of high power devices such as ultrasonic motors or micro-pumps, transformers etc. When the PZT ceramic resonated, the magnitude of the voltage across PZT ceramics decreased. We compared the voltage drop with the actual input voltage and represented the voltage reduction ratio as shown below. This equation relates to the impedance drop characteristics of the specimens.

$$\text{Voltage reduction ratio (\%)} = \frac{\text{Input voltage} - \text{voltage at the resonance frequency}}{\text{Input voltage}}$$

Reduction ratio of the specimen of 28 mm in diameter shows about 91.7% under 1 V_{rms}/mm and 5.6% under 25 V_{rms}/mm.

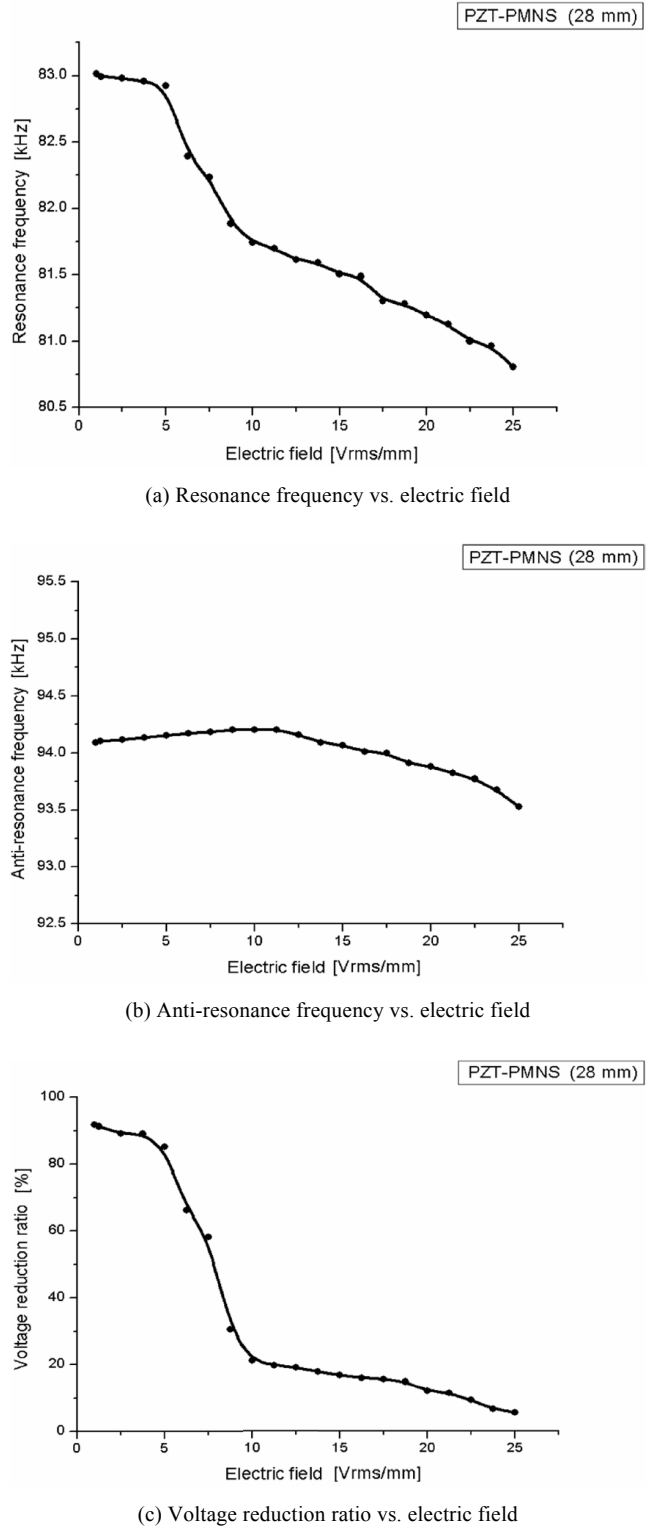


Fig. 3. Resonance characteristics of specimen. PZT: piezoelectric, PMNS: polynomial modular number system.

3.3 Electric field - PZT constants d_{33} variation

Figure 4 shows variation of PZT constant d_{33} for two cases. We calculated d_{33} using the resonance method of the IRE standards [2]. Overall, as the electric field increased, the PZT constants increased. However, a non-linear characteristic was revealed in a portion of range of the magnitude of

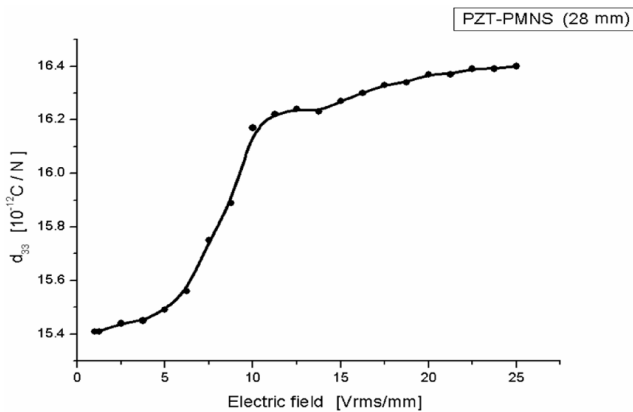


Fig. 4. Relation between PZT constant and electric field. PZT: piezoelectric, PMNS: polynomial modular number system.

the electric field. When the AC electric field, lower than the coercive field, was pushed in the polarized PZT ceramics, the domain of the grain changed and the strain of the PZT ceramics occurred. Hence, from the experimental results, the stacks and tendency which PZT constant increases shows that a difference exists in the shift of grain boundaries under low electric fields of nearly $1 \text{ V}_{\text{rms}}/\text{mm}$ and over $10 \text{ V}_{\text{rms}}/\text{mm}$. The observed increase in the d_{33} is likely due to the larger extrinsic contribution resulting from increased domain switching under the larger electric fields [8].

4. CONCLUSIONS

Sherrit *et al.* [9] and Takahashi *et al.* [10] reported that mechanical factors had greater effects on the non-linearity than the electrical factors. In this experiment, an notable mechanical vibration factor, which exerted its influence on the PZT characteristics, was generated in the specified electrical realm. If the input voltage on the poled PZT

ceramics increases, the vibration also axiomatically gets bigger at the resonance point. However, the vibration characteristics of PZT-PMNS ceramics are divided at the range of input voltages between 5 V_{rms} and $10 \text{ V}_{\text{rms}}$. These could be ascertained by the non-linear change of the frequency, voltage drop and PZT constant d_{33} . Because many applications such as PZT motor, pump and transformer etc. have a higher operational voltage level that the voltage used in this experiment, the variable tendencies of all of the above mentioned factors may be obvious.

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