Transactions of the Materials Research Society of Japan 29[4] 1171-1174 (2004)

Nonlinear Characteristics of Piezoelectric Ceramics

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A novel method for nonlinear piezoelectric characteristics measurement is proposed. A piezoelectric bimorph was prepared and driven around at a frequency which is 1/3 of its lowest order resonance frequency. Its displacement was measured with a laser Doppler vibrometer, and its frequency spectrum was analyzed. The third harmonic component of displacement showed resonance characteristics with changing its amplitude and its phase against the frequency. This phenomenon was applied to evaluate nonlinear characteristics of piezoelectric ceramics. The third order nonlinear displacement fraction could be obtained with changing the frequency and the amplitude of the electric fields. A fully electrical evaluation method for nonlinear piezoelectric characteristics was possible, and it could detect a small nonlinear component less than 0.1%.

Keywords: nonlinear, piezoelectric, spectrum analysis, PZT

1. INTRODUCTION

Piezoelectric ceramics have been widely used in actuator or ultrasonic transducer applications, such as ink-jet printing heads or piezoelectric transformers. In these applications, piezoelectric ceramics generate large strain and do not act as linear actuators or vibrators. The nonlinear characteristics of the piezoelectric ceramic materials significantly affect the performance of these devices. It is very important to know the nonlinear characteristics of the piezoelectric ceramic materials in order to design the device applications.

There are several studies[1-6] on the nonlinear characteristics of piezoelectric ceramic materials. One of the simplest ways to evaluate the nonlinear characteristics is a direct displacement measurement with changing amplitude of an electric field statically[1]. However, in this method, a high voltage needs to be applied to the specimens. Moreover, it is necessary to pay much attention to the sample holding conditions.

Another way to evaluate the non-linearity of the piezoelectric ceramic is analyzing its harmonic resonance[4,5]. Several researchers have worked on this harmonic resonance analysis. However the third harmonic resonance frequency is different from the fundamental resonance in term of vibration mode. The third harmonic resonance frequency is also different from the frequency which is three times its fundamental resonance frequency. These differences make the nonlinear characteristics evaluation complicated.

The authors had studied the nonlinear characteristic of the piezoelectric ceramic materials. Characteristic nonlinear phenomenon was observed when the piezoelectric plate was driven at frequencies lower than its lowest resonance frequency. In this frequency range, the harmonic mode individually shows a resonance behavior. The authors attempted to introduce a new method for the non-linearity evaluation for the piezoelectric materials by using this characteristic phenomenon. In this paper, the authors describe that the characteristic nonlinear phenomenon and discuss on the evaluation method for the nonlinearity of piezoelectric materials.

2. EXPERIMENTAL PROCEDURE

2.1 Measurement for displacement of bimorph

Piezoelectric bimorph actuators were made of the typically utilized a piezoelectric ceramic material for actuator applications, of which composition is expressed as

$$0.2Pb(Ni_{1/3}Nb_{2/3})O_3 - 0.8Pb(Ti_{0.50}Zr_{0.50})O_3.$$

Its relative dielectric permittivity and piezoelectric constant d_{31} are 2560 and -250pm/V, respectively. The bimorph used in the experiment was fabricated by the conventional tape casting method and co-firing technique. Its structure is schematically shown in Figure 1. The effective length and total thickness are 30mm and 0.3mm, respectively. Electrodes are co-fired platinum.

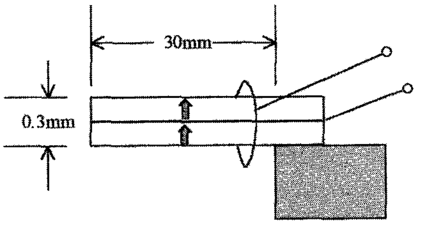

Fig.1 Schematic view of the bimorph specimen

Displacement of bimorph was measured as a cantilever type actuator by a laser Doppler vibrometer (Ono-Sokki LV-1610) with changing frequency.

2.2 Simple plate piezoelectric vibrators

The piezoelectric simple plate vibrators are made of two materials with different chemical compositions. One is so-called a soft PZT of which composition is same as the above composition, and the other is so-called a hard PZT, of which composition is expressed as

$$Pb(Ti_{0.48}Zr_{0.52})O_3 + 1wt\% \ Fe_2O_3$$

Its relative dielectric permittivity was 1400, and piezoelectric constant d_{31} was 130. Electric current was measured with changing amplitude of applied electric field and driving frequency below its resonance frequency of the length mode vibration. Dielectric measurement was done with an impedance analyzer (Hewlett-Packard: HP4294A), and nonlinear characteristics were analyzed with a spectrum analyzer (Agilent: 4395A)

3. RESULTS AND DISCUSSION

3.1 Bimorph actuation

The measured resonance frequency of the cantilever type bimorph was 145Hz. The authors observed the relation between displacement and voltage with changing frequency. Figure 2 shows their frequency dependences.

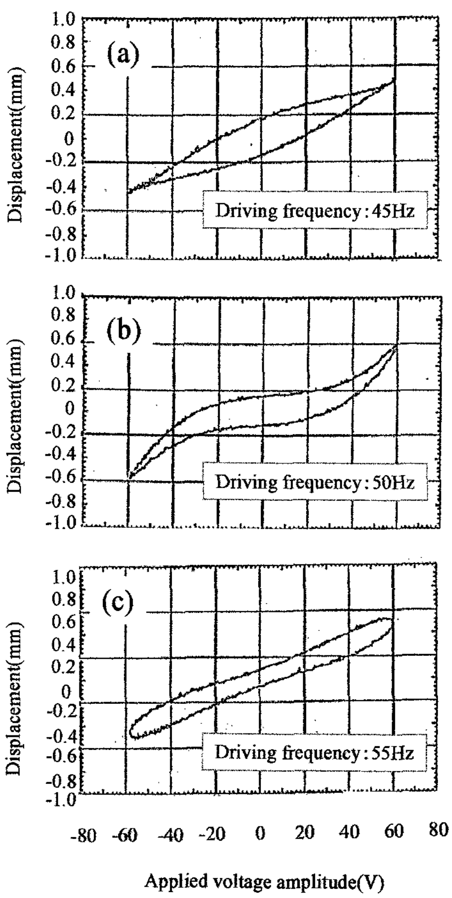

Fig.2 Frequency dependence of relation between displacement and applied voltage

Characteristic nonlinear phenomenon is found around a frequency which is one third the resonance frequency. The authors denote this frequency as $f_{1/3}$. Driving the bimorph at the frequency $f_{1/3}$, the resonance frequency component is superposed as the third harmonic vibration.

Then rough fittings were attempted for these characteristic nonlinear phenomena. The measured displacements were plotted against time, and these were compared to the calculated ones from the formula below with changing its amplitude A and phase Δ.

Displacement $\delta = C\cdot(\sin(\omega t) + A\cdot\sin(3\omega t-\Delta))$

C: Constant

Here the example of Fig.2(b) is taken and shown in Fig.3. When the A and Δ values are 0.25 and 150°, respectively, the measured displacement is well fitted by the calculated line.

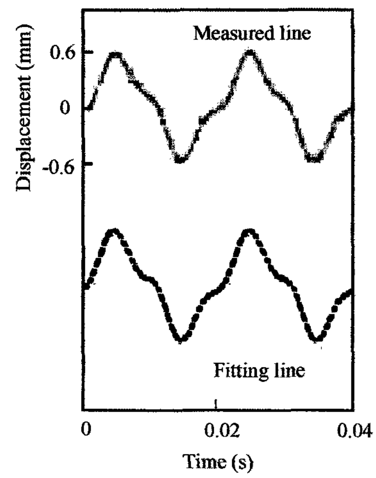

Fig.3 Displacement of the bimorph driven at 50Hz
The fitting line is expressed as
$\delta = 0.5\cdot(\sin(360\cdot50\cdot t) + 0.25\cdot\sin(3\cdot360\cdot50\cdot t - 150°))$

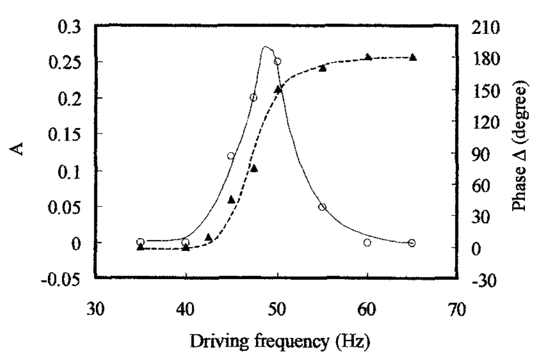

Fig.4 Resonance characteristics of the third harmonics

Figure 4 shows the A and Δ values estimated from the fitting plotted against the driving frequency. The A value makes a clear peak and Δ changes its value from 0° to 180° around the driving frequency of $f_{1/3}$. The third harmonic frequency component looks as if it individually shows a typical resonance behavior, in spite of no significant change of the driving frequency component.

3.2 Spectrum analysis of the length mode vibration

The length mode vibrations of the soft and hard PZT plates were investigated. Their resonance frequencies were 110kHz and 67kHz, respectively, and the plates were driven at frequencies around each frequency, which is one third of each resonance frequency. The measurement system setup is schematically shown in Fig.5.

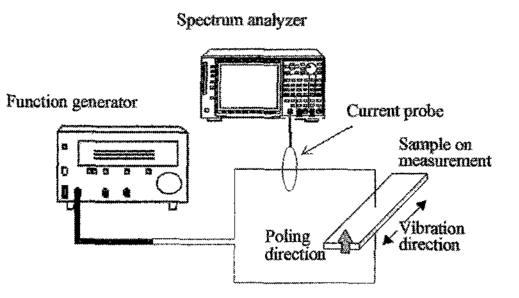

Fig.5 Measurement system setup for the length mode vibration

Electric current was measured and their frequency spectrums were analyzed. In case that the plate was driven at the one third the resonance frequency, the frequency spectrum shows a clear peak of the third harmonic frequency component as shown in Fig.6. Electric field amplitude was 35kV/mm there.

Analyzing this frequency spectrum, the nonlinear characteristics can be evaluated. It is shown in the next section.

3.3 Calculation procedure of the nonlinear components

Firstly it is necessary to know the clamped capacitance of specimen. It is calculated from free capacitance and electromechanical coupling coefficient.

The specimen is driven at the frequency $f_{1/3}$ which is one third of the resonance frequency. The current passing through the specimen is measured.

The measured current was decomposed to frequency components, namely, the driving frequency $f_{1/3}$ and its second harmonic frequency $f_{2/3}$ and its third harmonic frequency which is the resonance frequency fr.

The driving frequency component of the motional current was calculated by subtracting the displacement current from the driving frequency component of the measured current. Other frequency components are generated from the motion of the specimen, then, they compose the motional current.

When the driving frequency is changed around $f_{1/3}$, a significant change is observed in amplitude of the third harmonic frequency component. It shows a clear peak at fr with changing a phase. A Q value was obtained from the peak height and the 3dB width as shown in Fig.7. The obtained Q value was 410 there.

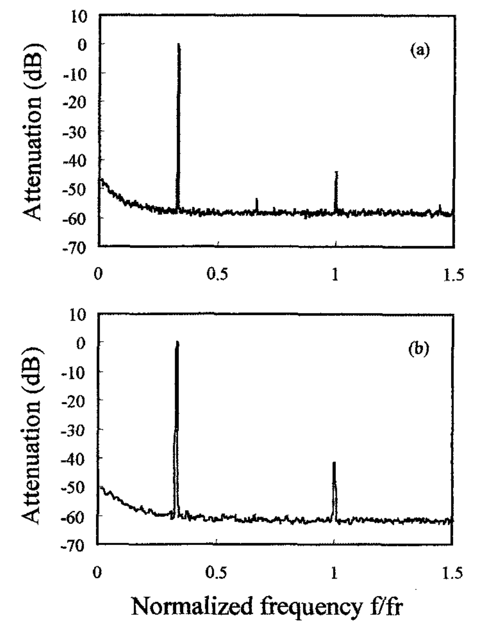

Fig.6 Frequency spectrums of Electric current: The soft PZT (a), and the hard PZT (b). Their resonance frequencies are 110kHz and 67kHz, respectively.

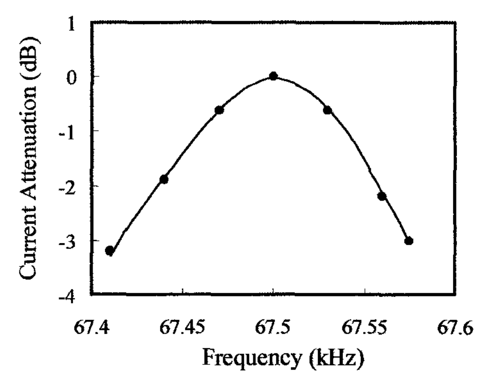

Fig.7 Resonance characteristics of Current

Dividing the peak height by the Q value, the amplitude of the third harmonics vibration at non-resonant condition can be obtained.

The third harmonic frequency component superposes onto the driving frequency component. It can be taken as the nonlinear component of displacement against applied electric field. When the driving frequency is low enough, the displacement behavior can be treated as its static behavior. The third order nonlinear coefficient has opposite sign to the liner coefficient in case that the plate becomes softer with increasing an applied electric field.

These procedures are repeated with changing amplitude of applied electric field. The Data used for the fundamental and the third harmonic frequency components are tabulated in Table 1.

Table 1 Data used for calculating the non-linearity of the piezoelectric ceramic plates

Material	Soft PZT	Hard PZT
Dimension (mm)	13·3·0.6	25·5·1
Free Capacitance C (nF)	1.47	1.70
Electromechanical coupling coefficient k_{31} (%)	40.6	32.2
Resonance Frequency (kHz)	110	67
Q_m	20	410
Motional Current I_{m1} (mA)	1.15	0.87
Motional Current I_{m3} (μA)	1.23	0.40
Curie temperature (°C)	280	340

Q_m: Mechanical quality factor calculated from the 3dB width of the third harmonic component
k_{31}: Calculated by the resonance-antiresonance method
I_{m1}: The fundamental frequency component of the montional current at 35kV/mm
I_{m3}: The third frequency component of the montional current at 35kV/mm

The fundamental and the third harmonic frequency components are plotted against the electric field. It is shown in Fig.8.

Slopes for the fundamental and third harmonic frequency components against electric field shown in Fig.8 are 1 and 3 for the logarithmic plot, respectively. It means that the third harmonic frequency component is proportional to cubic electric field. Then, the authors conclude that the third order nonlinear characteristics can be evaluated by the third harmonic frequency component analysis. The nonlinear component fractions for the soft and hard PZT at the electric field of 35kV/m are estimated as 0.11% and 0.046%, respectively.

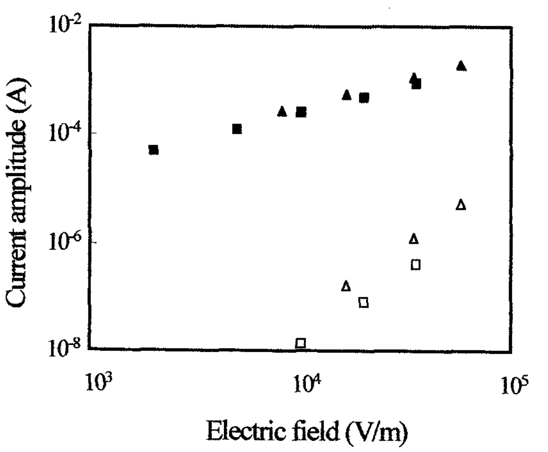

Fig.8 Electric field dependence of current amplitude at non-resonance state.

- ▲ Fundamental mode(soft PZT)
- ■ Fundamental mode (hard PZT)
- △ The 3rd harmonics (soft PZT)
- □ The 3rd harmonics (hard PZT)

In order to obtain the nonlinear piezoelectric characteristics, the measured current is divided by the vibrating frequency, because the current is proportional to the vibration velocity. Then the fraction of the nonlinear component to the total displacement can be obtained. If the piezoelectric constant d_{31} is known with a small signal measurement, the displacement at a large electric field can be estimated by using the d_{31} at the small signal and the obtained nonlinear fraction.

However, the supposed method cannot indicate a sign of the third order nonlinear coefficient. It is necessary to know the sign of the nonlinear coefficient by other means such as a measurement of phase difference between the fundamental and the third harmonic vibration. In the case of the bimorph mentioned above, the third harmonic coefficient is a positive value. This means that the third order nonlinear coefficient is a negative value. On the contrary, the author assumed that the third order nonlinear coefficient for the simple plate vibration is positive, because a resonance frequency lowers with increasing applied electric field amplitude for usual PZT cases[6].

This evaluation method for nonlinear piezoelectric properties is convenient because it is fully electrical, and does not need a high voltage or high power source. Moreover, it can detect a small fraction of a nonlinear component less than 0.1%. The author believes that the proposed method is very effective to know the nonlinear characteristics of piezoelectric materials. A rough estimation of nonlinear characteristics is easily carried out with the simple measurement setup. without vagueness such as approximations for solving nonlinear differential equations.

4. CONCLUSIONS

The Author described the characteristic nonlinear phenomenon of a piezoelectric ceramic plate observed at frequencies below its resonance frequency. Driving the plate around at $f_{1/3}$, the third harmonic vibration showed a clear resonance, individually. The author also showed the spectrum analysis for the harmonic mode vibration, and proposed a novel method for evaluating the nonlinear characteristics of piezoelectric ceramics. It could detect a small nonlinear component less than 0.1%.

5. REFERENCES

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(Received October 11, 2003; Accepted March 10, 2004)