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Jump Phenomena of Current in Piezoelectric-ceramic Vibrators Under High Power Conditions

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Abstract

In order to investigate the origin of current-jump phenomenon when piezoelectric-ceramic vibrators were driven at high power levels, the influence of higher harmonics due to the ferroelectric nonlinearity on the jump phenomenon was studied. Using the equivalent circuit equation including a higher harmonic term, the theoretical calculation was performed. Since the calculated values of current under jump phenomena agree well with the measured ones, the jump phenomenon is due to the higher harmonics caused by ferroelectric nonlinearity. It was also found that the strain jump phenomenon appears when the jump of current occurs around the resonance frequency. © 1999 Elsevier Science Limited. All rights reserved

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1 Introduction

A running stability under high power driving is strictly required in piezoelectric ceramics for high power operation such as piezoelectric transformers or piezoelectric vibrators used for ultrasonic cleaners and machining cutters. In addition to heat generation and mechanical breakdown, jump phenomenon of the current is also a factor obstructing the stable operation. Although the appearance of the jump phenomenon was frequently described in previous reports,[1,2] there are no papers previously that described the generation mechanism or the origin of the jump phenomenon. We reported that the higher harmonics due to ferroelectric nonlinearity was observed when the piezoelectric ceramics were driven at high power levels.[3] Since the higher harmonics always appeared in the sample when the jump phenomenon was observed, the relation between the jump phenomena and higher harmonics was examined in this paper. This examination showed that experimental data of jump phenomena correspond to the theoretical values calculated from the circuit equation including the term of higher harmonics. Furthermore, we describe how the jump phenomenon of the strain was also observed with the current jump phenomenon.

2 Experimental

The composition of the prepared ceramics is as follows.

$$0{\cdot}95\mathrm{Pb}(\mathrm{Zr}_{0\cdot51}\mathrm{Ti}_{0\cdot49})\mathrm{O}_3 \\ -0{\cdot}05\mathrm{Pb}(\mathrm{Sb}_{0\cdot5}\mathrm{Nb}_{0\cdot5})\mathrm{O}_3 + 0{\cdot}01\mathrm{MnCO}_3$$

The starting materials are extra-pure Pb_3O_4, ZrO_2, TiO_2, Sb_2O_3, Nb_2O_5 and $MnCO_3$. The sample was prepared by means of a conventional method.[4] The sample configuration was a rectangular bar, as shown in Fig. 1. The electromechanical coupling factor, mechanical quality factor, and elastic resonance frequency of the sample measured using an LF impedance analyzer (HP, 4192A) under a small signal field at room temperature, are 0·35, 1270, and 34·7 kHz respectively. The sample was a 'hard-material' with a high mechanical quality factor.

The sample voltage and current were monitored using a digital storage scope (IWATSU, ST3711). For measurement of the vibration amplitude, a noncontact fiberoptic displacement meter (IWATSU ST-3711) was employed. The details of

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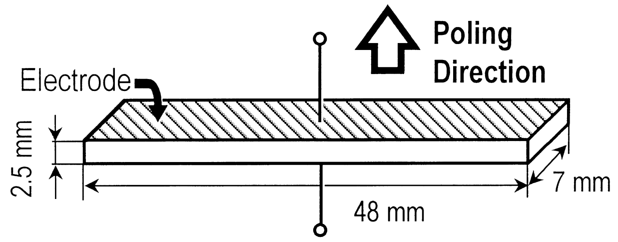

Fig. 1. Geometry of the piezoelectric ceramic vibrator.

the measurements method are described in previous papers.[3,4]

3 Results and Discussion

3.1 Jump phenomena

The frequency response of current was studied when the samples were driven at a constant voltage around the resonance frequencies. Figure 2 shows the relation between the frequency and the current when a sample was driven at constant voltages of 0·2 and 4·4 V. When the applied voltage was lower than 1 V, the typical resonance-current spectrum was observed as shown by the solid curve in Fig. 2, and the spectrum shape is symmetric with respect to the resonance frequency. With the increase of applied voltage, the shape of current spectrum became unsymmetric. In the lower frequency side than the resonance frequency, the rate of increase or decrease in the current became larger compared with the rate in the higher frequency side. When the applied voltage increased up to 2·5 V, the jump phenomena appeared, and the hysteresis was observed in the current spectrum as shown by the broken curves in Fig. 2. When the frequency was increased from the lower frequency side to higher frequency side, the magnitude of the current suddenly jumped from point A to B, and simultaneously the current phase jumped from lead phase to lagging phase. After that, the current decreased smoothly, and reached C point. On the other hand, when the frequency was decreased from the C point, the current continuously increased even after passing point B, and suddenly dropped down from point D to E. The current phase changed from lagging phase to lead phase at the same time. The voltage waves were maintained to be sinusoidal during the measurements.

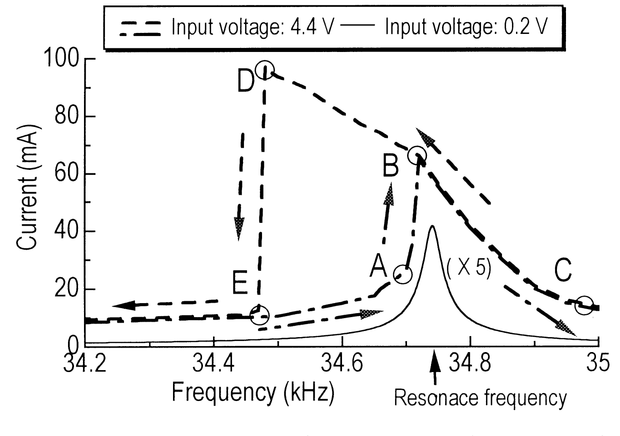

Fig. 2. Frequency response of current around resonance frequency.

Since, in general, the current of piezoelectric ceramics has a linear relation to the sample strain around the resonance frequency, it is expected that the jump phenomenon is also observed in the strain. In order to investigate the strain behavior when the current-jump phenomenon occurs, the displacement of the end surface in the length direction was measured. As shown in Fig. 3, the similar frequency responses of displacement were observed. Thus, since the strain-jump phenomenon appeared clearly near the resonance frequency, a high power driving around the resonance frequency makes the precise strain control difficult, although the precise strain control is practically indispensable for piezoelectric ceramics.

It has been reported that the jump phenomenon with respect to frequency as shown in Figs 2 and 3 were observed in elastic materials having the property called ‘soft spring’ when they were driven at a constant stress.[5] The origin of the current-jump phenomenon had been considered to be the elastic softening from the analogy to the property of ‘soft spring’.[2] However, it is difficult to believe the mechanism of ‘soft spring’ in piezoelectric ceramics, since it has never been demonstrated by experimental results. Hence, we tried to explain the origin of this jump phenomenon by means of higher harmonic voltages generated in piezoelectric ceramics instead of the softening.

3.2 Nonlinear piezoelectricity and circuit equation

We found that the higher harmonic voltages, which come from ferroelectric nonlinearity, were observed when piezoelectric ceramics vibrators were driven at high power levels around the resonance frequency with a constant-current method.

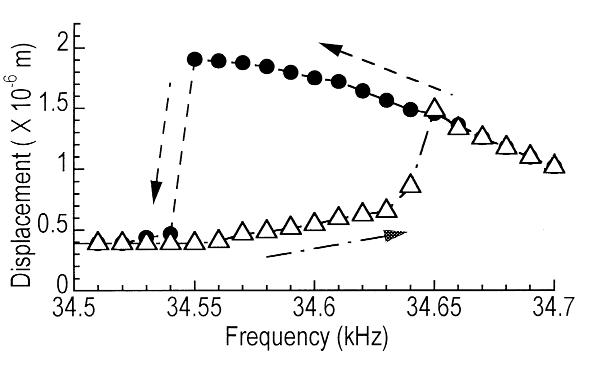

Fig. 3. Frequency response of displacement at the end surface of the vibrator around resonance frequency.

The magnitudes of 2nd and 3rd harmonics are proportional to the square and cube of current density as shown in Fig. 4. From these results, the electric field E is expressed by adding these higher harmonics represented by electric flux density to the linear piezoelectric h-equation as shown by eqn (1).

$$E = -h_{31}S_1 + \beta_{33}D_3 + \gamma_{33}D_3^2 + \xi_{33}D_3^3 \quad (1)$$

where, h_{31} are piezoelectric h constant, β_{33}, S_1, D_3, E are inverse permittivity, strain, electric flux density, applied field, and both γ_{33} and ξ_{33} are nonlinear coefficients, respectively. Since the contribution of the $\gamma_{33}D_3^2$ term is small enough to be negligible compared with the $\xi_{33}D_3^3$ term as described in Fig. 4, eqn (1) is simplified as eqn (2).

$$E = -h_{31}S_1 + \beta_{33}D_3 + \xi_{33}D_3^3 \quad (2)$$

Equation (2) indicates that the electric field of the sample consists of the 3rd harmonics element $\xi_{33}D_3^3$ and a linear part $-h_{31}S_1 + \beta_{33}D_3$ of the piezoelectric equation. Since it is permitted to show the linear part using an LCR equivalent circuit, the following equation is obtained.

$$L\frac{\mathrm{d}i}{\mathrm{d}t} + Ri + \frac{1}{C}\int i\mathrm{d}t + \xi'_{33}\left(\int i\mathrm{d}t\right)^3 = v \quad (3)$$

Here, the sample current $i = \mathrm{d}q/\mathrm{d}t$, electric charge $q = AD$, $\xi'_{33} = t\xi_{33}/A^3$, A is electrode surface area, t is sample thickness, L, C, R are inductance, resistance, capacitance of the equivalent circuit. The fourth term in the left side of eqn (3) comes from the third higher harmonic voltage, and when the current becomes larger, the contribution of the fourth term can not be ignored.

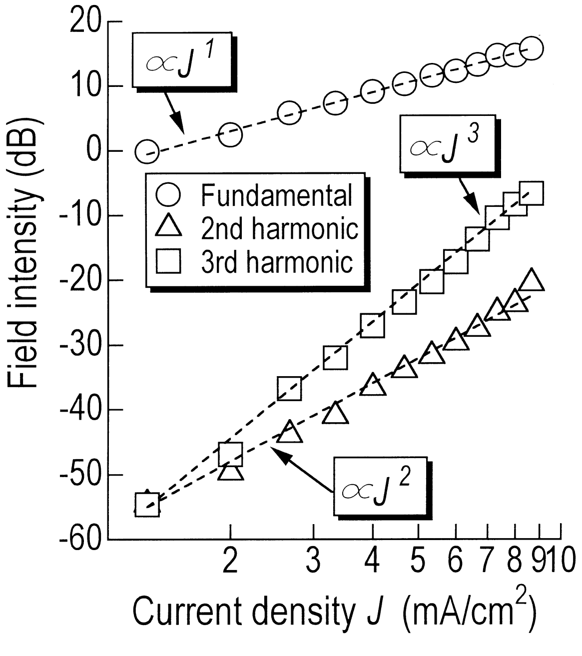

Fig. 4. Fundamental, 2nd, and 3rd harmonic voltages as a function of current density at resonance frequency. The broken lines are drawn by assuming power law of $\propto J$,$\propto J^2$, and $\propto J^3$.

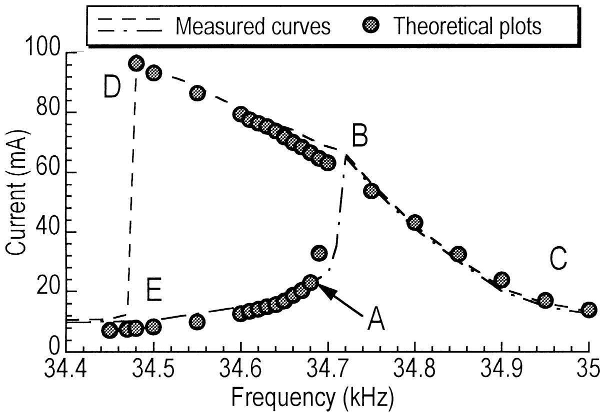

Fig. 5. Theoretical plots of frequency response of current.

We tried to compare current values shown in Fig. 2 with theoretical ones calculated with this equation. Since it is difficult to analytically solve eqn (3) for the current, we employed the numerical approximation, in which the current is approximated by $i = i_0 \sin \omega t$.[5] Consequently, the following equation is obtained.

$$\frac{3\xi'_{33}}{4\omega^3}i_0^3 = \left(\omega L - \frac{1}{\omega C}\right)i_0\pi \pm \sqrt{v_0^2 - R^2 i_0^2} \quad (4)$$

When the relation between current and frequency is expressed by eqn (4), the current jump phenomenon occurs at a specific frequency.[5] The jump phenomenon appear in the frequency region lower than the resonance frequency when ξ'_{33} is negative, and it appears in the higher frequency region when ξ'_{33} is positive.[5] As shown in Fig. 2, since the current jump phenomenon was observed at frequencies lower than the resonance frequency, ξ'_{33} is negative. The absolute value of ξ'_{33} was calculated using the frequency and current at the point A in Fig. 2 where the jump phenomenon exactly occurred. The values of L, C, and R were measured using an LF impedance analyzer (HP, 4192A) under a small signal field. By graphically solving eqn (4) for i_0, we can draw the theoretical frequency response of the current as described in Fig. 5. Since the theoretical plots agree well with the experimental broken lines, it was found that the 3rd harmonic voltage causes the current-jump phenomenon.

4 Conclusion

The 3rd harmonic voltage due to the ferroelectric nonlinearity induces the jump phenomena of current and strain around the resonance frequency when the piezoelectric ceramics were driven at high power levels. This was confirmed by the theoretical calculation using the equivalent circuit equation including a higher harmonic term.

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