3J1-4

The relationship between piezoelectric high power property and linear property

圧電材料ハイパワー特性と線形パラメータの関係性

Susumu Miyake[1†], Takashi Kasashima[2], Masato Yamazaki[2], Yasuyuki Okimura[2], Hajime Nagata[3] and Takeshi Morita[1] ([1] Graduate School of Frontier Sciences, The Univ. of Tokyo; [2]NGK SPARK PLUG Co., Ltd.; [3]Tokyo Univ. of Science)
三宅 奏 [1†]，笠島 崇 [2]，山崎 正人 [2]，沖村 康之 [2]，永田 肇 [3]，森田 剛 [1] ([1] 東京大学大学院 新領域創成科学研究科, [2] 日本特殊陶業株式会社, [3] 東京理科大学)

1. Introduction

For the high power ulatrasonic applications using piezoelectric materials, nonlinear piezoelectric vibration is significant problem because it comes down to the limitation of the vibration velocity. It is originated from the mechanical nonlinearity rather than the dielectric and piezoelectric nonlinearities[1]. It indicates that large strain magnifies the influence of the higher order elasticity. Therefore, the higher order elastic constant is suitable for evaluating the piezoelectric nonlinear vibration.

Our research group has already improved the piezoelectric LCR equivalent circuit for describing the nonlinear vibration[1]. The nonlinear resistance and the nonlinear capacitor were introduced. Using this model, the higher order elastic constant of the piezoelectric material can be obtained by admittance curve fitting. This method requires only admittance curve measurement; therefore, it enables to evaluate piezoelectric high power characteristics effectively.

In this study, the higher order elastic constants of $Pb(Zr,Ti)O_3$ ceramics, $(1\text{-}x)Ba(Zr,Ti)O_3\text{-}x(Ba,Ca)TiO_3$ ceramics, $(K, Na)NbO_3$ ceramics and $LiNbO_3$ single crystal were evaluated and compared.

2. Nonlinear model

2.1 Higher order elasticity

Piezoelectric equation of 31 effect with higher order elasticity is expressed as equations (1)-(2)[2]:

$$T_1 = \overline{c_{11}^E} S_1 + \overline{c_{11(3)}^E} S_1^3 + \overline{e_{31}} E_3 \tag{1}$$

$$D_3 = \overline{e_{31}} S_1 + \overline{\varepsilon_{33}^S} E_3 \tag{2}$$

where T_1, S_1, E_3, D_3 are strain, stress, electric field and electric flux density; $\overline{c_{11}^E}$, $\overline{c_{11(3)}^E}$, $\overline{e_{31}}$, $\overline{\varepsilon_{33}^S}$ are linear elastic constant, cubic elastic constant, piezoelectric constant and dielectric constant. The higher term $\overline{c_{11(3)}^E} S_1^3$ is considered. Other higher terms are omitted because the even-ordered term doesn't affect the signal with driving frequency and the influence of more than 5th order terms is negligible. In this research, cubic elastic constant $\overline{c_{11(3)}^E}$ was measured and utilized for evaluating piezoelectric high power characteristics. $\overline{c_{11(3)}^E}$ was treated as complex number as equation (3):

$$\overline{c_{11(3)}^E} = \mathrm{Re}\left(\overline{c_{11(3)}^E}\right) + j\mathrm{Im}\left(\overline{c_{11(3)}^E}\right) \tag{3}$$

2.2 Equivalent circuit model[1]

The relationship between voltage V and current i_m in the mechanical part of piezoelectric LCR equivalent circuit is given as equation (4):

$$L\frac{di_m}{dt} + R_0 i_m + \frac{1}{C_0}\int i_m dt = V \tag{4}$$

where L, R_0 and C_0 are equivalent mass, dumping and compliance. Under high power condition, the relationship is expressed as equation (5):

$$L\frac{di_m}{dt} + R_0 i_m + \eta i_m^3 + \frac{1}{C_0}\int i_m dt + \xi\omega^3\left(\int i_m\, dt\right)^3 = V \tag{5}$$

where ω is driving angular frequency; ξ and η are nonlinear coefficients which represent nonlinear elasticity. These nonlinear coefficients can be obtained by the curve fitting to the measured admittance curve using equation (5).

The relationship between cubic elastic constant $\overline{c_{11(3)}^E}$ and nonlinear coefficient ξ and η is expressed as equations (6)-(7):

$$Re\left(c_{11(3)}^E\right) = \frac{16}{9}\frac{\overline{c_{11}^E}^2 A^2}{\rho\omega_r L}\xi \tag{6}$$

$$Im\left(c_{11(3)}^E\right) = \frac{16}{9}\frac{\overline{c_{11}^E}^2 A^2}{\rho\omega_r L}\eta \tag{7}$$

where A, ρ, ω_r are force factor, density and angular resonance frequency.

3. Measurement

In this research, we investigated high power characteristics of following piezoelectric materials.

(1) $Pb(Zr,Ti)O_3$ ceramics
(2) $(1\text{-}x)Ba(Zr,Ti)O_3\text{-}x(Ba,Ca)TiO_3$ ceramics
(3) $(K, Na)NbO_3$ ceramics
(4) $LiNbO_3$ single crystal

miyake@ems.k.u-tokyo.ac.jp

Table 1 Parameters of measured piezoelectric transdcers

No.	Material	Q_m	Width [mm]	Thickness [mm]	Length [mm]	No.	Material	Q_m	Width [mm]	Thickness [mm]	Length [mm]
1	PZT	2100	6.0	2.0	24.0	14	KNN	60	3.3	1.5	11.0
2		2010	6.0	2.0	24.0	15		150	3.2	1.5	11.9
3		1860	6.0	2.0	24.0	16		410	2.7	1.0	11.9
4		890	2.7	1.0	16.0	17		450	3.5	1.4	11.1
5		1370	2.7	1.0	15.9	18		210	3.1	1.2	12.2
6		830	2.7	1.0	15.9	19		90	3.3	1.0	12.0
7		930	2.7	1.0	16.0	20		60	3.0	1.0	12.0
8		100	6.0	2.0	24.0	21		60	3.0	1.0	12.0
9	BZT-BCT	150	3.0	1.0	12.0	22		60	3.0	1.0	12.0
10		420	3.0	1.0	12.0	23		100	3.3	1.4	11.3
11		1320	3.0	1.0	12.0	24		70	2.8	1.1	15.9
12	KNN	70	3.2	1.5	11.2	25	LN	11300	7.0	0.5	44.0
13		70	3.4	1.1	11.1						

We prepared plate type transducers of these piezoelectric materials with various mechanical quality factor Q_m as shown in **Table 1**. Measuring the longitudinal vibration of plate type transducer by 31 effect, $\overline{c^E_{11(3)}}$ was obtained. Measurement of piezoelectric ceramics (1)-(3) were conducted with admittance curve measurement with frequency response analyzer (NF FRA5097) and curve fitting using equivalent circuit model[1]. Measurement of (4) $LiNbO_3$ single crystal was conducted with electrical transient response measurement[3]. It is because the transducer was corrupted due to the long excitation of admittance measurement.

The relationship between $1/\mathrm{Im}\left(\overline{c^E_{11(3)}}\right)$ and $\overline{c^E_{11}}$, d_{31} of piezoelectric ceramics are shown in **Fig. 1-2**. $\mathrm{Im}\left(\overline{c^E_{11(3)}}\right)$ decreased as $\overline{c^E_{11}}$ increased and d_{31} decreased. It indicates that hardening of piezoelectric ceramics reduces the influence of nonlinear elasticity. It is also evident from the relationship between $\overline{c^E_{11(3)}}$ and $MnCO_3$ content of BZT-BCT ceramics, which is shown in **Fig. 3**. However, $\overline{c^E_{11}}$ and d_{31} of PZT are saturated but BZT-BCT's and KNN's doesn't saturated in Fig.1-2. These results verified that the lead-free piezoelectric ceramics could be improved their nonlinear effect by modifying their linear coefficients like PZT. Measured minimum $\overline{c^E_{11(3)}}$ of each piezoelectric material are shown in **Table 2**. Absolute value of $\overline{c^E_{11(3)}}$ of LN single crystal is outstanding compared to PZT, BZT-BCT and KNN. It is because of the structure of single crystal; namely, grain boundary has great influence to nonlinear elasticity.

4. Conclusion

In this research, high power characteristics of piezoelectric materials are evaluated with higher order elastic constant. It reveals the hardening of piezoelectric materials reduces the piezoelectric nonlinear vibration.

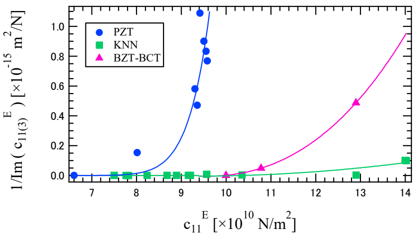

Fig. 1 The relationship between $1/\mathrm{Im}\left(\overline{c^E_{11(3)}}\right)$ and $\overline{c^E_{11}}$

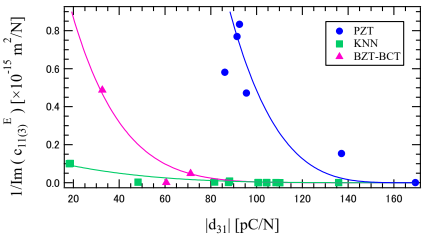

Fig. 2 The relationship between $1/\mathrm{Im}\left(\overline{c^E_{11(3)}}\right)$ and d_{31}

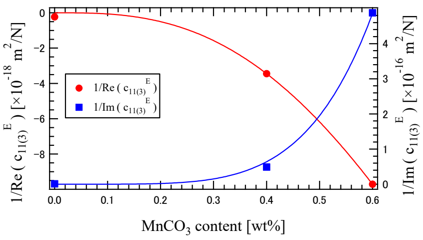

Fig. 3 The relationship between $\overline{c^E_{11(3)}}$ of BZT-BCT and $MnCO_3$ content

Table 2 Measured minimum $\overline{c^E_{11(3)}}$ of each material

	$\mathrm{Re}\left(\overline{c^E_{11(3)}}\right)$ [N/m^2]	$\mathrm{Im}\left(\overline{c^E_{11(3)}}\right)$ [N/m^2]
PZT	-9.6×10^{15}	1.2×10^{15}
BZT-BCT	-1.0×10^{17}	2.1×10^{15}
KNN	-3.3×10^{16}	9.9×10^{15}
LN	6.6×10^{13}	4.1×10^{13}

References

1. Y. Liu, R. Ozaki and T. Morita: *Sens. Actuat. A*, **277** (2015) 31-38.
2. T. Morita: *Piezoelectric Phenomena* (Morikita Press, Tokyo, 2017) 109-112.
3. M. Umeda, K. Nakamura and S. Ueha: *Jpn. J. Appl. Phys.* **38** (1999) 5581-5585