Characterisation of a Lead-free Piezoceramic for Application in Power Ultrasonic Transducers

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Abstract. A lead-free piezoceramic, sodium bismuth titanate (NBT), was characterised to obtain all the independent elastic, piezoelectric and dielectric (EPD) properties, and as a piezoceramic with C∞/6mm symmetry, the EPD matrix is populated by five elastic, three piezoelectric and two dielectric coefficients. Being a new material, the complete EPD matrix is required for transducer design, however, due to poling challenges only three of the four resonant mode samples were available for the IEEE characterisation technique. The IEEE technique was combined with the Levenberg–Marquardt (LM) optimisation algorithm to determine the ten EPD coefficients, by using impedance magnitude data from a miniature sample, and EPD values from the IEEE technique as input for the LM algorithm. The piezoelectric and dielectric values determined by both techniques are in strong agreement with each other and with the data available in literature.

Introduction

Piezoelectric material is the principal source of ultrasound in power ultrasonic transducers. Lead zirconate titanate (PZT), a lead-based piezoelectric ceramic, or piezoceramic, is the piezoelectric material most commonly used in power ultrasonic surgical devices [1]. However, due to the adverse effect of lead on human health and the environment and legislation relating to its use in devices, there is an increasing demand for lead-free piezoelectric materials [2]. The performance of power ultrasonic devices relies on the independent elastic, piezoelectric and dielectric (EPD) properties of the piezoceramic used. Piezoceramics have a C∞/6mm symmetry [2, 3] and EPD properties are governed by constitutive equations, as expressed in Eq. 1 and Eq. 2. Accurate estimations of the EPD properties are necessary in the design of power ultrasonic transducers, which usually relies on finite element analysis (FEA). These properties are determined from both established standard techniques [4] and newer proven techniques [2], to populate the full 3-dimensional (3D) matrix Eq. 3.

$$T = c^E S - eE \tag{1}$$
$$D = eS + \varepsilon^S E \tag{2}$$

Where S, strain, T, stress, E, electric field and D, dielectric displacement, with c^E, stiffness elastic coefficients, e, piezoelectric constants, and ε^S, dielectric constants. Superscript indices E and S are constant electric field and constant strain, respectively.

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} c_{11}^E & c_{12}^E & c_{13}^E & 0 & 0 & 0 & 0 & 0 & e_{31} \\ c_{12}^E & c_{11}^E & c_{13}^E & 0 & 0 & 0 & 0 & 0 & e_{31} \\ c_{13}^E & c_{13}^E & c_{33}^E & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44}^E & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & 0 & c_{44}^E & 0 & e_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{15} & 0 & \varepsilon_{11}^S & 0 & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 & 0 & \varepsilon_{11}^S & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 & 0 & 0 & \varepsilon_{33}^S \end{bmatrix} . \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{3}$$

In piezoceramics belonging to the C∞/6mm class of symmetry, nearly 70% of the coefficients in the 3D matrix are zero. Furthermore, the matrix is symmetrical about its main diagonal and, as a result, the number of independent EPD coefficients in the matrix is reduced from forty-five to ten and are categorised as 5 elastic, 3 piezoelectric, and 2 dielectric coefficients.

Material and Method

Determination of the independent EPD properties of piezoceramics using experimental techniques, such as the IEEE standard for electrical impedance spectroscopy, or a mix of experiment and optimisation algorithm, is known as material characterisation. The lead-free material being characterised is a sodium bismuth titanate (NBT), $(Na_{0.5}Bi_{0.5})TiO_3$ composition, and is named as Pz12 (CTS Ferroperm, Denmark). Table 1 and Fig. 1 show the dimensions and the samples used in the experiments, respectively, where sample geometries (aspect ratios) were guided by the IEEE standard.

Only three of the four resonant modes required for complete characterisation by the IEEE technique were available due to poling challenges, namely thickness extensional (TE), thickness shear (TS) and length thickness extensional (LTE). The length extensional (LE) mode is currently not available. The three resonant mode samples shown in Fig. 1 were first characterised using an Impedance Analyser (Agilent 4395A) to obtain the impedance magnitude and phase data. Then, using the Piezoelectric Resonance Analysis Program (PRAP), a commercial curve fitting software, some of the EPD coefficients were obtained from this experimental data. To resolve the incomplete resonant mode challenge, a miniature sample in Fig.1 with dimensions estimated from FEA modelling, was diced from the LTE mode sample. The impedance magnitude of the miniature sample was measured. Data from this measurement and EPD values estimated using the IEEE technique, were used to carry out a characterisation using an optimisation algorithm based on the Levenberg-Marquardt technique.

Name	Dimension [mm]
Radial/TE (disc)	d = 20; **t** = 0.5
TS	l = 10; w = 10; **t** = 0.94
LTE	l = 10; w = 3; **t** =1
Miniature	l = 3; w = 3; **t** = 1

*TE = thickness extensional; TS = thickness shear
LTE = length thickness extensional

Table 1: Pz12 dimensions; poling direction in red

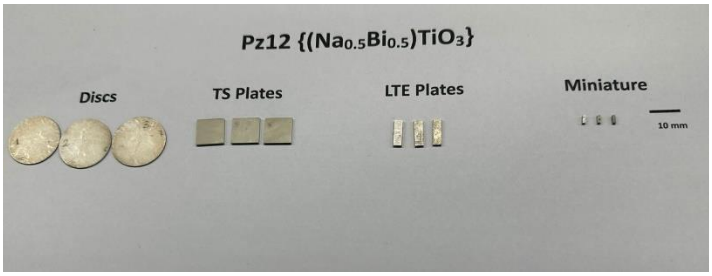

Figure 1: Piezoceramic Samples for Experimental Characterisation

Results and Discussion

The results obtained by experimental measurements in accordance with the IEEE standards and by a combination of experiment and Levenberg–Marquardt algorithm (LMA), are displayed in Table 2. The values of the EPD properties determined by both techniques align with those of similar piezoceramics available in literature. The piezoelectric and dielectric values closely match when compared, however, the elastic properties had differences ranging from 9–19%. The Impedance Analyser's fixture is bigger than the miniature sample, causing heavy damping, thus, impacting the acquired impedance magnitude. The LMA is a minimum local finder which relies on the initial estimates and impedance magnitude data used in optimisation, these factors are probable causes for the difference in elastic property values.

	Property	IEEE	LMA
$\times 10^{10}$ [N/m²]	c_{11}^E	11.70	13.68
	c_{12}^E	-4.47	-3.39
	c_{13}^E		0.712
	c_{33}^E		13.28
	c_{44}^E	5.52	6.05
	c_{66}^E	4.64	5.55
[C/m²]	e_{31}	-0.89	-0.91
	e_{33}		11.22
	e_{15}	4.31	4.32
$/\varepsilon_0$	ε_{11}^S	533	532
	ε_{33}^S	527	529

Table 2: EPD properties obtained from experiment and LMA

Conclusion

The purpose of this work is to characterise a lead-free piezoceramic and fully populate its EPD matrix. This was achieved by combining the IEEE standard and LMA techniques. Future work to be carried out include constructing a bespoke fixture for the miniature sample, validation of all results and poling the LE mode sample.

References

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