Loss mechanisms and high power piezoelectrics

International Center for Actuators and Transducers, Penn State University, University Park, PA, USA

S. HIROSE
Faculty of Eng., Yamagata University, Yonezawa, Japan

Heat generation is one of the significant problems in piezoelectrics for high power density applications. In this paper, we review the loss mechanisms in piezoelectrics first, followed by the heat generation processes for various drive conditions. Heat generation at off-resonance is caused mainly by dielectric loss tan δ (i.e., P-E hysteresis loss), not by mechanical loss, while the heat generation at resonance is mainly attributed to mechanical loss tan φ. Then, practical high power materials developed at Penn State is introduced, which exhibit the vibration velocity more than 1 m/s, leading to the power density capability 10 times of the commercially available “hard” PZTs. We propose a internal bias field model to explain the low loss and high power origin of these materials. Finally, using a low temperature sinterable “hard” PZT, we demonstrated a high power multilayer piezoelectric transformers.

© 2006 Springer Science + Business Media, Inc.

1. Introduction

Loss or hysteresis in piezoelectrics exhibits both merits and demerits. For positioning actuator applications, hysteresis in the field-induced strain provides a serious problem, and for resonance actuation such as ultrasonic motors, loss generates significant heat in the piezoelectric materials. Further, in consideration of the resonant strain amplified in proportion to a mechanical quality factor, low (intensive) mechanical loss materials are preferred for ultrasonic motors. To the contrary, for force sensors and acoustic transducers, a low mechanical quality factor Qm (which corresponds to high mechanical loss) is essential to widen a frequency range for receiving signals.

K. H. Haerdtl wrote a review article on electrical and mechanical losses in ferroelectric ceramics [1]. Losses are considered to consist of four portions: (1) domain wall motion, (2) fundamental lattice portion, which should also occur in domain-free monocrystals, (3) microstructure portion, which occurs typically in polycrystalline samples, and (4) conductivity portion in highly-ohmic samples. However, in the typical piezoelectric ceramic case, the loss due to the domain wall motion exceeds the other three contributions significantly. They reported interesting experimental results on the relationship between electrical and mechanical losses in piezoceramics, Pb0.6La0.4(Zr0.3Ti0.7)xMe2O3, where Me represents the doped ions Mn, Fe or Al and x varied between 0 and 0.09. However, they measured the mechanical losses on poled ceramic samples, while the electrical losses on unpoled samples, i.e., in a different polarization state, which lead big ambiguity in the discussion.

Authors are aware little systematic studies of the loss mechanisms in piezoelectrics, particularly in high electric field and high power density ranges. Although T. Ikeda described part of the formulas of this paper in his textbook [2], he totally neglected the piezoelectric losses, which have been found not to be neglected in our investigations. In this paper, we review the loss mechanisms in piezoelectrics first, followed by the heat generation processes for various drive conditions. Then, practical high power materials developed at Penn State are introduced, exhibiting the power density capability 10 times of the commercially available “hard” PZTs. We propose a model to explain the low loss and high power origin of these materials.
Finally, using a low temperature sinterable “hard” PZT, we demonstrated a high power multilayer piezoelectric transformers.

The terminologies, “intensive” and “extensive” losses are introduced in the relation with “intensive” and “extensive” parameters in the phenomenon. These are not directly relevant with “intrinsic” and “extrinsic” losses which were introduced to explain the loss contribution from the mono-domain single crystal status and from the others [3]. In this paper, our discussion is focused on the “extrinsic” losses, in particular, domain-reorientation originated losses.

2. General consideration of loss and hysteresis in piezoelectrics

2.1. Theoretical formulas

Since we have described the detailed mathematics in the previous paper [4], we just summarize the results in this section. We start from the following two piezoelectric equations:

\[ x = s^E X + d E, \]
\[ D = d X + b^E E. \]

Here, \( x \) is strain, \( X \), stress, \( D \), electric displacement, \( E \), electric field. Equations 1 and 2 are the expression in terms of intensive (i.e., externally controllable) physical parameters \( X \) and \( E \). The elastic compliance \( s^E \), the dielectric constant \( b^E \) and the piezoelectric constant \( d \) are temperature-dependent. Note that the piezoelectric equations cannot yield a delay-time related loss, without taking into account irreversible thermodynamic equations or dissipation functions, in general. However, the latter considerations are mathematically equivalent to the introduction of complex physical constants into the phenomenological equations, if the loss is small and can be treated as a perturbation.

Therefore, we will introduce complex parameters \( s^{E*} \), \( b^{E*} \) and \( d^* \) in order to consider the hysteresis losses in dielectric, elastic and piezoelectric coupling energy:

\[ s^{E*} = s^E(1 - j \tan \delta'), \]
\[ b^{E*} = b^E(1 - j \tan \phi'), \]
\[ d^* = d(1 - j \tan \theta'). \]

\( \theta' \) is the phase delay of the strain under an applied electric field, or the phase delay of the electric displacement under an applied stress. Both delay phases should be exactly the same if we introduce the same complex piezoelectric constant \( d^* \) into Equations 1 and 2. \( \delta' \) is the phase delay of the electric displacement to an applied electric field under a constant stress (e.g., zero stress) condition, and \( \phi' \) is the phase delay of the strain to an applied stress under a constant electric field (e.g., short-circuit) condition. We will consider these phase delays as “intensive” losses.

Fig. 1a–d correspond to the model hysteresis curves for practical experiments: \( D \) vs. \( E \) curve under a stress-free condition, \( x \) vs. \( X \) under a short-circuit condition, \( x \) vs. \( E \) under a stress-free condition and \( D \) vs. \( X \) under a short-circuit condition for measuring current, respectively. Notice that these measurements are easily conducted in practice.

The stored energies and hysteresis losses for pure dielectric and elastic energies can be calculated as:

\[ U_x = (1/2)e^{E*} e_0 E_0^2, \]
\[ w_x = \pi e^{E*} e_0 E_0^2 \tan \delta', \]
\[ U_m = (1/2)b^{E*} X_0^2, \]
\[ w_m = \pi b^{E*} X_0^2 \tan \phi'. \]

The electromechanical hysteresis losses are more complicated, which can be calculated as follows, depending on the measuring ways; when measuring the induced strain under an electric field,

\[ U_{em} = (1/2)(d^2/s^E) E_0^2, \]

and

\[ w_{em} = \pi (d^2/s^E) E_0^2 (2 \tan \theta' - \tan \phi'). \]

Note that the strain vs. electric field measurement should provide the combination of piezoelectric loss tan \( \theta' \) and