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Evaluation of the mechanical quality factor under high power conditions in piezoelectric ceramics from electrical power

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Abstract

The main methods used to measure the mechanical quality factor in piezoelectric ceramics under high power resonance conditions are the electrical impedance method and the transient method. These methods are limited in their ability to provide relevant data from an application perspective because of the conditions under which the measurements must occur. In this research, a unique approach for characterizing the mechanical quality factor in piezoelectric materials has been developed. This method allows for the calculation of the quality factor from data at a single frequency, which is not possible with other methods. This technique has been applied to a hard PZT material for vibration conditions ranging from antiresonance to resonance at a vibration velocity of 100 mm/s RMS. Results from the quality factor measurement from impedance data and from the new method have a deviation of <2% at resonance, proving the validity of the new electrical power method.

Keywords: Piezoelectric; Mechanical quality factor; High power measurement; Lead zirconate titanate

1. Introduction

The properties of piezoelectric materials depend strongly on their operating and testing conditions. Many piezoelectric transducers operate in high power conditions, thus causing the need to measure piezoelectric properties under such circumstances [1]. Typical characterization techniques use lower power measurements, so researchers have developed specialized methods to characterize high power properties [2–4].

Among the most important high power properties of piezoelectric ceramics is the mechanical quality factor, Q_m, which is the inverse of the mechanical loss, $\tan\phi'$. Practically, the mechanical quality factor is an amplification factor of vibration of a piezoresonantor in resonance conditions. A high mechanical quality factor in PZT (lead zirconate titanate), or "hardness", is achieved by acceptor doping the system thereby generating internal field which suppresses domain wall motion. This is the main cause of mechanical loss in piezoelectric materials. [5].

There are two methods which are used to measure mechanical loss in high power resonance conditions: the impedance method and the burst/transient method. The impedance method requires the measurement of impedance data from a frequency sweep between resonance to antiresonance using a constant excitation condition, be it either voltage, current, power, or vibration velocity [1,6,7]. The other method of measuring the mechanical loss is through the burst or transient method. In this method, the sample is driven at high excitation voltage at its resonance frequency for a set number of cycles. After this, the excitation is removed and the sample is short circuited, and therefore the sample's oscillation rings down. By measuring the decay of current during the self vibration dampening, the mechanical loss can be calculated [2].

In this paper, a new method to measure the mechanical quality factor will be presented. It proceeds from a similar work of ours [8], where the quality factor was derived from mechanical relationships such that the mechanical quality factor could

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be calculated using temperature measurements. This research will prove that the quality factor can also be evaluated using the electrical power, which is a more simple approach than using temperature data to calculate the dissipated power by heat transfer. This new method is capable of measuring the quality factor before the onset of temperature rise due to heat generation (burst/transient method), and is capable of measuring the quality factor during continuous drive (impedance spectrum method). In general, the authors believe this to be the superior method to measure the mechanical quality factor in simple ceramic samples due to its flexibility, accuracy, and ease of implementation.

2. Theoretical treatment – derivation of the mechanical quality factor in terms of electrical power

In our previous work [8], we derived the relationship between the heat generated, the vibration velocity, and the mechanical quality factor in a longitudinally vibrating plate ceramic is

$$Q_m = 2\pi f \times \frac{\rho V_{RMS}^2}{h_g} \tag{1}$$

where ρ is the mass density, V_{RMS} is the tip RMS vibration velocity, and h_g is a parameter which characterizes the heat generation distribution. A similar derivation will be presented here, except in this case the quality factor will be derived in terms of electrical power.

The mechanical quality factor is defined as

$$Q_m = 2\pi f \frac{U_e}{P_d} \tag{2}$$

where U_e is the stored mechanical energy of the system and P_d is the power dissipated, the unit of which is watts [9]. $2\pi f$ is the angular frequency. In this case, the sample vibration is not externally restricted, therefore the power dissipated in the ceramic is equal to the input electrical power. Equivalently, the mechanical quality factor can be written in terms of energy and power density

$$Q_m = 2\pi f \frac{u_e}{p_d}. \tag{3}$$

The energy density as a function of vibration velocity for longitudinally vibrating piezoelectric plate is (k_{33}, k_{31}, k_t)

$$u_{e,l} = \frac{1}{2}\rho V_{RMS}^2. \tag{4}$$

Using this equation and Eq. (4), the quality factor for longitudinally vibrating piezoelectric plates can be written

$$Q_{m,l} = 2\pi f \frac{\frac{1}{2}\rho V_{RMS}^2}{P_d/(L\,w\,t)} \tag{5}$$

where L, w, and t are the dimensions of a rectangular plate. This equation can also be written in terms of the mass(m) of the sample, assuming that the sample is a perfect rectangular plate

$$Q_{m,l} = 2\pi f \frac{\frac{1}{2}m V_{RMS}^2}{P_d} \tag{6}$$

Using this equation, it is a simple task to investigate the quality factor behavior for a variety of conditions. The Q_m formulation seen in Eq. (5) can also be performed for other vibration types, such as radial and shear vibration if the relationship of vibration to mechanical energy is known. Experimental application of this method in comparison to the impedance spectrum method will be presented in the coming sections. Because the mechanical energy derivation used the mode shape at the resonance frequency to determine the energy density, the inherent assumption in the equations is that the mode shape is approximately equal to the mode shape at resonance. This limits the frequency bandwidth around the resonance at which the model is valid. We can assume for polycrystalline ceramics which have a low to medium coupling factor, k, the mode shapes at resonance and antiresonance are approximately the same [10]. This means the theory can be applied safely between resonance and antiresonance. In general, one must calculate the mode shape and the mechanical energy density to determine the relationship between the quality factor, tip vibration level and electrical input power. However, as stated, such calculations add insignificant value because for low to medium k materials the antiresonance and resonance mode shapes are approximately equivalent.

3. Experimental results using electrical power for Q_m

3.1. *Review of high power methods to measure* Q_m *in piezoelectric ceramics*

At present, there exist two methods of measuring the mechanical quality factor in high power conditions, namely the impedance method and the burst method.

The impedance method involves a frequency sweep across the resonance and antiresonance frequencies of a material at a constant excitation condition, be it constant voltage, constant current, constant power, or constant vibration velocity. The impedance response is then used to calculate the Q_m and other material parameters using a 3 db bandwidth calculation or equivalent circuit. Because the sample undergoes different vibration behavior under either constant voltage, current, and power when performing the frequency sweep, the impedance response can be skewed due to elastic nonlinearity, which indicates the material properties are changing during the measurement. Thus the measurement become less precise and is prone to more error. To solve this problem, the excitation condition of constant vibration velocity was introduced. In this way, the distorted impedance response was eliminated. However, as this research will prove, the material properties (e.g. Q_m) will still change, and thus even using this advanced control scheme, the data is still susceptible to some of the error plaguing the other control methods. Other setbacks of this method include inability to evaluate mechanical loss at a single frequency and the necessity of continuously driving the sample for several minutes during the course of the measurement. [1,6,7]

The other method of measuring the mechanical loss in high power conditions is through the burst or transient method. In this method, the sample is driven at very high excitation voltage at its resonance frequency for a set number of cycles. After this