Experimental Determination of Mechanical Quality Factor of Lead Zirconate Titanate (PZT-5A4E) by Equivalent Circuit Method under various Thermal and Resistance Conditions

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Abstract- Piezoelectric effect is a linear electromechanical effect between electrical and mechanical properties. In this research work, a specially designed apparatus was used to determine the mechanical quality factor of Lead Zirconate Titanate (PZT-5A4E) by shocking it at variable frequencies and resistances under various thermal conditions. Equivalent circuit method was used to determine the mechanical quality factor by shocking it at resonant frequency and anti-resonant frequency. It was found that with the increase in temperature and resistance mechanical quality factor decreases.

Keywords- PZT-5A4E, Resistance, Electromechanical Interaction, Frequency, Thermal Conditions.

I. INTRODUCTION

PIEZOELECTRIC materials are those which on the application of mechanical stress can produce electric voltage. Out of 32 known crystalline groups, 28 are piezoelectric in nature. The macroscopic behavior of the piezoelectric materials differs from that of individual crystallites, due to orientation of such crystallites [1]. The technique to convert mechanical input to electric output with the help of piezoelectric vibrator was developed [2]. Mechanical quality factor was declared as one of the most basic parameters for piezoelectric materials [3]. Piezoelectric materials are versatile that makes them unique from other crystals [4]. Thermal expansion is useful technique in piezoelectric materials rather than other solid materials [5]. Reference [6] determined mechanical impedance of piezoelectric material from the electrical impedance. Electric voltage generated by piezoelectric material depends on its boundary conditions as well as on its electrical conductivity [7]. Increase in the pressure applied causes reduction in piezoelectric area [8]. Reference [9] analyzed piezoelectric ring with high mechanical quality factor as a transformer at different temperatures to increase its efficiency at varying load conditions. Reference [10] optimized multi-layer newly doped factor that resonate at 1.7MHz and have a lot of applications as sensors and actuators. A new class of piezoelectric materials was introduced having high quality material for high power applications and high temperature applications [11]. Reference [12] developed piezoelectric materials and increased their mechanical quality factor at sintering temperature. Trends and behavior of a piezoelectric material as a ceramic at different temperatures were shown [13]. Reference [14] determined dynamic characteristic of piezoelectric material.

Our aim was to find out the mechanical quality factor at variable temperatures and resistances. Now a days field of Micro Electro Mechanical System is emerging, piezoelectric materials as a sensor and actuator has a vast role in it, so there characterization also plays a vital role in this field for smart structures.

II. MATERIAL

Lead zirconate titanate is a ceramic material that shows remarkable piezoelectric effect as compared to other ferroelectric properties. PZT develops a voltage difference across two of its faces when compressed (mostly used in sensor applications), and physically strained when an external electric field is applied (used for actuators etc). It is also ferroelectric, in other words, it has a spontaneous polarization which can be reversed in the presence of an electric field. The lead zirconate titanate is widely used in polycrystalline (ceramic) with very high piezoelectric coupling. Depending on the formula of preparation, PZT materials may have different forms and properties. Manufacturers of PZT use proprietary formulas for their products. Techniques that are commonly used for preparing the bulk PZT materials such as (PZT-4, PZT-5) are not suited for micro-fabrication. A number of techniques for preparing PZT films have been demonstrated, including sputtering, laser ablation, jet molding, and electrostatic spray deposition. Lead zirconate titanate shows much greater piezoelectricity effect than quartz. These can readily be fabricated into variety of shapes and sizes and therefore can be tailored to a particular application. Dimensions of the specimen used are provided in Table I while the piezoelectric, mechanical and thermal properties are provided in Table II.

TABLE I
DESCRIPTION OF SPECIMEN (PZT-5A4E SINGLE LAYER DISKS)

Composition	Trade	(Dimension)		Part No
		Diameter	Thickness	
Lead Zirconate Titanate	PiezoSystems Inc.	12.7mm	0.191mm	T107-A4E-273

TABLE II
PARENT SPECIMEN PROPERTIES

Sr #	Description	Notation	Value	Units
Piezoelectric Properties				
01	Relative Dielectric Constant @1KHz	K^T_3	1800	
02	Piezoelectric strain coefficient	d_{33}	390×10^{-12}	Meters/Volt
03		d_{31}	-190×10^{-12}	Meters/Volt
04	Piezoelectric voltage coefficient	g_{33}	24×10^{-3}	Volt meters/Newton
05		g_{31}	-11.6×10^{-3}	Volt meters/Newton
06	Coupling coefficient	K_{33}	0.72	
07		k_{31}	0.32	
08	Polarization field	E_p	2×10^6	Volts /meter
09	Initial depolarization field	E_c	5×10^5	Volts/meter
Mechanical				
10	Density	P	7800	Kg/meter^3
11	Mechanical Q	Q	80	
12	Elastic modules	Y^E_3	5.2×10^{10}	Newtons/meter^2
13		Y^E_1	6.6×10^{10}	Newtons/meter^2
Thermal				
14	Thermal expansion coefficient		$\sim 4 \times 10^{-6}$	Meters/meter °C
15	Curie Temperature		350	°C

III. EXPERIMENTAL SETUP

The experimental setup consisted of a load cell fixed with the base of mild steel sheet, the square shaped specimen was fixed with nut and bolt on the load cell in such a way that it's lower and upper both sides face copper electrodes as anode and cathode. To perform electrical and thermal insulation mica sheet was used which is resistant to both electrical and thermal conductivity. For the sake of on spot heating we used heat filament element in a circuit and to observe the temperature, temperature gun is used. The response is analyzed on digital oscilloscope at different temperatures. Experimental setup and overall circuit diagram are shown in Fig. 1 and Fig. 2 respectively.

Fig.1. Experimental Setup

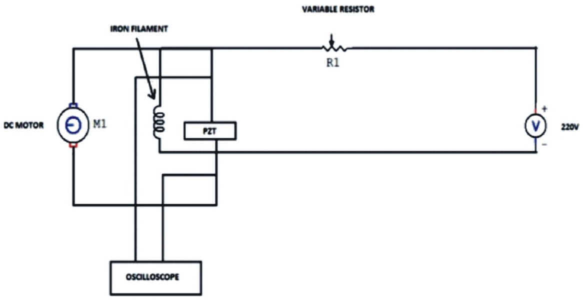

Fig. 2. Circuit diagram for the experimental setup

We applied sinusoidal waveform to shock the piezoelectric material.

The calculations for prediction of mechanical quality factor are given in equations 1, 2, and 3.

$$Qm=Xc/R \quad (1)$$

As impedance is

$$Xc= 1/(2\pi fC) \quad (2)$$

So eq. (1) Becomes

$$Qm=1/(2\pi fRC) \quad (3)$$

Where "f" is average frequency of resonant frequency fa and anti-resonant frequency fb. As shown in Fig. 3.

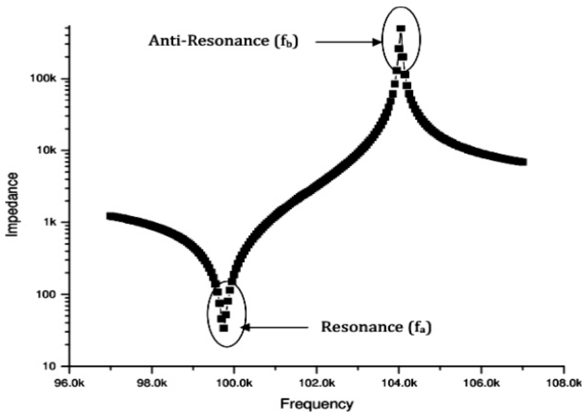

Fig. 3. Impedance curve of piezoelectric material showing resonance and anti-resonance

IV. Results And Discussions

Experiments were performed at variable temperatures ranging from 20 °C to 200 °C. The mechanical quality factor was found to be decreased with the increase in temperature showing 2^{nd} order polynomial behavior as shown in Fig. 4.

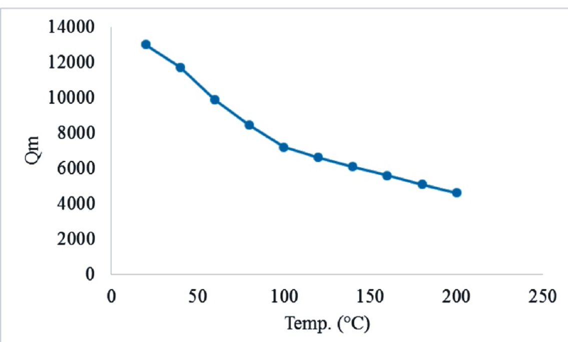

Fig. 4. Prediction of Mechanical Quality Factor of a piezoelectric material under variable Temperature

It is observed that on increasing the resistance at constant temperature conditions (initially at 20 °C and then at 100 °C, the mechanical quality factor decreases accordingly. Resistance was varied from 5 K ohm to 82 K ohm and its response was observed on the oscilloscope. 3^{rd} order polynomial behavior was observed as shown in Fig. 5 and Fig. 6.

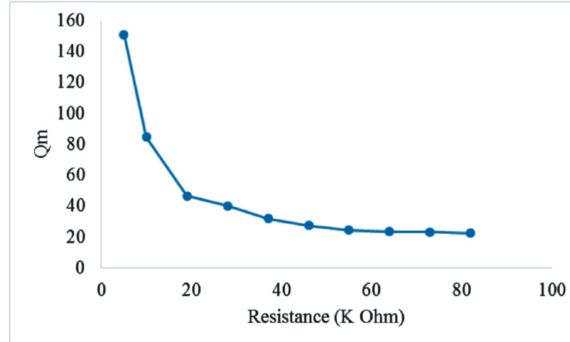

Fig. 5. Mechanical Quality Factor of a piezoelectric material under 20°C Temperature and Variable Resistance

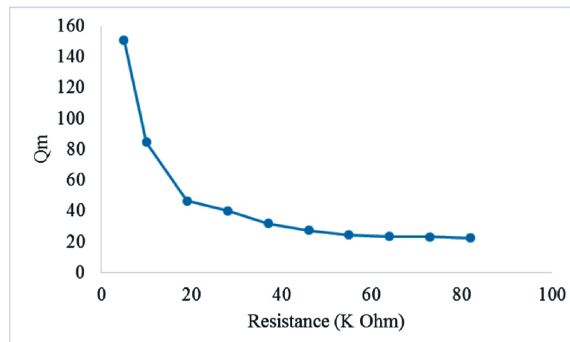

Fig. 6. Mechanical Quality Factor of a piezoelectric material under 100°C Temperature and Variable Resistance

Similar behavior was observed at a constant temperature of 180^0C as shown in Fig. 7.

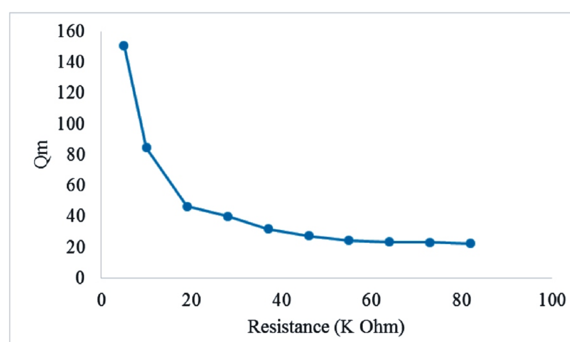

Fig. 7. Mechanical Quality Factor of a piezoelectric material under 180°C Temperature and Variable Resistance

V. Conclusions

Following are the conclusions obtained from the current research work:

1. With the increase in temperature up to Curie temperature the mechanical quality factor of Lead Zirconate Titanate decreases as a linear function.

2. Negative linear behaviour is observed between temperature and Qm as well as for resistance because effect of polarization.
3. For best performance and for maximum mechanical quality factor use pzt at 20 °C temperature, 0 Ohm resistance, and 200 Hz frequency because of dipolar motion of its ions. So it is highly applicable to use Lead Zirconate Titanate at low temperature, low resistance and high frequency for maximum results.

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