Effect of Temperature and Pressure on the Thickness Mode Resonant Spectra of Piezoelectric Ceramic

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Abstract: Piezoelectric Lead Zirconate Titanate (PZT) ceramics based acoustic transducers are widely used in a multitude of applications as sensors and actuators. Different modeling techniques are used by transducer designers to test the original designs without building costly prototypes. The equivalent circuit of piezoelectric vibrator represented by Van Dyke model is used to plot the resonant curve. Based on the application, piezoelectric materials in the acoustic transducers are subjected to a variety of environmental conditions. This results in the shift in the resonant frequency. This paper reports the effect of change in temperature and pressure on the thickness mode response of equivalent circuit of piezoelectric Lead Zirconate Titanate (PZT) ceramic. The ranges considered are suitable for under water applications. With varying conditions of temperature and pressure, the changes in resonant and anti-resonant frequencies of the piezoelectric material are noted. Using these practically obtained values, parameters of the model are computed and the shift in the resonance curve is observed for the conditions considered. The values of resonant and anti-resonant frequencies obtained from the model response match with those obtained experimentally for the given conditions. Other material constants required for building realistic Finite Element Analysis models can be computed using these practically obtained values of resonant and anti-resonant frequencies.

Keywords: Piezoelectric ceramic, Process parameter modeling, resonant spectra, thickness mode vibration.

1. INTRODUCTION

Acoustic transducers which use Lead Zirconate Titanate (PZT) ceramic as the piezoelectric material are widely used in various applications. Mathematical modelling plays an important role in designing these transducers. It helps to meet the specifications in a shorter time [1]. The Van Dyke model which represents the equivalent circuit of piezoelectric vibrator is used to plot the resonant curve [2-4]. Accuracy of the model depends on the accuracy of the material properties. These properties depend on process conditions prevailing in the given application. Therefore the useful approach would be to characterize the materials under the exact conditions of their use. The results thus obtained can be used in designing the transducers [5]. Acoustic transducer used for underwater applications is subjected to considerable temperature and pressure variations below the surface of water [6-9]. PZT is the most commonly used piezoelectric material. This material has been a subject of intensive investigation and study of change in its material constants with temperature and pressure is widespread [10-13]. In most of
the references the temperature ranges considered are high as found in some non-destructive testing and sonar applications. Also the stress is on dependence of material constants on the process conditions. In the references on equivalent circuit of piezoelectric vibrator [2-4] dependence of model response on process conditions is not considered. This paper reports a study of the temperature and pressure dependence of thickness mode response of equivalent circuit of piezoelectric LeadZirconateTitanate (PZT) ceramic. The application considered for the conditions of temperature (minimum of 5°C and maximum of 40°C) and pressure (maximum of 1 kg.cm⁻²) is open channel flow measurement. For the said application the transducer is immersion type. So the temperature and pressure conditions are that of water. There is a change in the temperature and pressure conditions is not considered. This paper reports a change in the thickness mode resonant and anti-resonant frequencies with changing temperature and pressure conditions. The parameters of the equivalent circuit are found out using these practical values of thickness mode resonant and anti-resonant frequencies, and the shift in the thickness mode resonance curve is observed.

The paper is organized as follows: Section on theory and related work first discusses the theory related to equivalent circuit of piezoelectric element which is followed by the work carried out in this field. The experimentation section reports the samples and the experimental setup used to acquire the observations. This section also outlines the procedures followed. The observations made are presented and discussed in the section on results and discussions. In the last section, the findings, inference drawn and the future work are given.

2. THEORY AND RELATED WORK

For sensing applications, it is convenient to fit the impedance plots to lumped circuit models in order to predict the electrical behavior of the resonator [2]. The Van Dyke circuit model recommended by IEEE standard on piezoelectricity is widely used for representing the equivalent circuit of a piezoelectric vibrator and is as shown in fig. 1[6-9]. In the Van Dyke model, four real circuit parameters C₀, C₁, L₁ and R₁ represent the impedance of the piezoelectric resonator at resonance.

![Figure 1: Van Dyke model.](image)

The branch with capacitance C₀ represents the electrical nature of the piezoelectric disc whereas the branch with components R₁, L₁, and C₁ represents the mechanical behavior of the piezoelectric disc. In this equivalent circuit the resonant (f_r), anti-resonant (f_a) frequencies and C₁ are given by (1), (2), and (3):

\[
f_r = \frac{1}{2\pi \sqrt{C_1L_1}}
\]

(1)

\[
f_a = \frac{1}{2\pi \sqrt{\frac{c_0c_1}{c_1+c_0}L_1}}
\]

(2)
The characterization of piezoelectric ceramics is done using the resonance method as mentioned in the IEEE standard on piezoelectricity. A small ac electrical signal is used to excite an elastic wave in the piezoelectric via an electromechanical coupling. Depending on the sample dimensions, the frequency at which resonance occurs is observed by measuring the impedance of the sample at various frequencies. Depending on the vibration mode, the frequency range usually used is from 10 kHz to 6 MHz [10]. Measurement of capacitance $C_o$ is done at 1 kHz using capacitance meter. In [5], the authors have presented temperature (-5°C to 125°C) and pressure (0 to 20 MPa) based characterization of piezoelectric single crystal material (PMN-PT) for applications such as non-destructive testing at high temperatures and underwater sonar applications. The parameters analyzed are the permittivity ($\varepsilon_{33,s}$), coupling co-efficient ($k_s$), electric displacement ($c_{33,D}$), and piezoelectric stress constant ($\varepsilon_{33}$). The authors of [11] studied the changes in electromechanical coupling factor ($k_p$), mechanical quality factor ($Q_m$), relative dielectric constant ($\varepsilon_r$), charge constants ($d_{13}$ and $d_{31}$) of soft PZT material with changing temperature conditions (room temperature to the Curie point). In [12], the authors measured the impedance spectra of lead zirconate titanate ceramic samples for a temperature range of 0°C to 100°C. They determined the elastic, dielectric, and piezoelectric constants. This work was extended for the temperature range of -165°C to 195°C in [10]. The authors of [13] presented the effect of change in temperature (-55°C to 85°C) on piezoelectric coefficient ($\varepsilon_{31, f}$) of lead zirconate titanate (PZT) thin films. In [14], the authors have plotted the impedance frequency plot for a temperature range of 25°C to 200°C with the PZT element operated in radial mode. The authors of [15], developed a new force resonant sensor whose natural frequency is a function of the applied force. In our previous work [16], the change in the resonant and the anti-resonant frequencies for a temperature range of 5°C to 40°C in steps of 5°C was studied. Also the change in the resonant and the anti-resonant frequencies for a pressure range of 0 to 1 kg.cm⁻² in steps of 0.04 kg.cm⁻² was studied.

### 3. EXPERIMENTAL ARRANGEMENTS

PZT 5 type piezoelectric ceramic disks from Sparkler Ceramics Ltd, India were used as samples for the experimentation. The piezoelectric disks had a diameter of 25 mm, a thickness of 2 mm, and a diameter to thickness ratio of 12.5. The flat surfaces of the samples are coated with silver electrodes to facilitate ohmic contact for measurement of electric properties [17].

A temperature controlled water bath was used to study the effect of change in temperature on the resonant and anti-resonant frequency. The set up consists of a temperature controlled water bath, circuit [18] consisting of signal generator and oscilloscope, and an insulated PZT disc. The temperature of water bath is controlled using time duplex control strategy. A stirrer is used to keep the temperature uniform. To prevent heat loss to the atmosphere, the water bath is thermally insulated. A heater and cooling jacket is used to maintain the temperature of the water bath. A thermocouple is used to measure the temperature of the water bath. The minimum and the maximum temperatures considered are 5°C and 40°C respectively. The setup is as shown in fig. 2.

The selection of the temperature range is as per the application considered. The temperature is varied from minimum to maximum values in steps of 5°C. The values of the resonant and
For open channel flow metering the transducer is located at maximum 10m below the water surface [19]. The head pressure acting on the transducer affects its resonant frequency. A height of 10 m of water creates a head pressure of approximate 1 kg.cm$^{-2}$.

Weights calibrated in terms of pressure were used for simulating the head pressure acting on the transducer. The weight to be applied to the disc is calculated based on the maximum pressure considered and the area of the disc. The details are included in our previous work [16]. For generating a pressure of 1 kg.cm$^{-2}$ the weight that is applied to PZT 5 of 25 mm diameter is 4.9087 kg. The pre-calibrated weights are applied to the piezoelectric disc and the values of resonant and anti-resonant frequencies are observed using the circuit shown in fig. 2.

4. RESULTS AND DISCUSSIONS

The resonant and anti-resonant frequencies of PZT 5 measured at temperatures 5°C and at 40°C are used for calculating the values of equivalent circuit model using equations (1), (2) and (3). The table of the values of resonant, anti-resonant frequencies and equivalent circuit model parameters for PZT 5 for changing temperature conditions are tabulated in Table I.

**Table I: Effect of Temperature on Equivalent Circuit Model**

| Material | Temperature (°C) | Equivalent circuit parameters | Frequencies |
|----------|------------------|------------------------------|-------------|
|          |                  |                              | Resonant    | Anti-resonant |
| PZT5     | 5                | $C_0 = 195$ pF, $C_1 = 572.73$ F, $L_1 = 48.151$ µH, $R_1 = 3.5$ Ω | 958.1 kHz   | 1.09 MHz      |
|          | 40               | $C_0 = 195$ pF, $C_1 = 542.405$ pF, $L_1 = 51.013$ µH, $R_1 = 4$ Ω | 956.5 kHz   | 1.082 MHz     |

Sufficient soaking time is provided. Experiment is repeated for 10 times and average values are computed. Here readings for the minimum and maximum temperatures are reported. The changes in resonant frequencies for other readings are reported in our previous work [16].
Also at No Load and Full load conditions, the resonant and anti-resonant frequencies of PZT 5 were observed and similar calculations are done. The table of the values of resonant, anti-resonant frequencies and equivalent circuit model parameters for pressure characterization are given in Table II. Based on these practically obtained model parameters, mathematical modeling using equivalent circuit approach was implemented in Simulink. Simulink allows to build models, simulate, and analyze them using simple click and drag procedures. Electrical circuits can be built using SimPowersystems tool box. A graphical user interface for the steady state analysis of electrical circuits is obtained using powergui block in this toolbox. The Impedance versus frequency measurement tool dialog box displays the impedance versus frequency. The model build is shown in fig. 3.

The change in the responses of the model with change in temperature (minimum of 5°C and maximum of 40°C) is shown in fig. 4a and fig.4b respectively. A decrease in resonant frequency is observed with increase in the temperature. For the given temperature range, the change in resonant frequency is 1.6 kHz. 1.6 kHz in 957 kHz is 0.17%. The resonant frequency of the piezoelectric element is directly proportional to stiffness constant [20]. There is a decrease in the stiffness of the piezoelectric element with increase in temperature. So the resonant frequency decreases with increase in temperature.

The change in the response of the model with change in pressure (No Load and Full Load) is shown in fig.5a and fig.5b respectively. As the pressure increases, the resonant and the anti-resonance frequencies increase.

| Material Load Condition | Equivalent Circuit Parameters | Frequencies |
|-------------------------|------------------------------|-------------|
|                         |                              | Resonant    | Anti-resonant |
| PZT5 No Load            | $C_o = 195 \text{ pF}$      | 954.7 kHz   | 1.086 MHz     |
|                         | $C_1 = 569.763 \text{ pF}$  |             |              |
|                         | $L_1 = 48.75 \mu \text{H}$  |             |              |
|                         | $R_1 = 4 \Omega$            |             |              |
| Full Load               | $C_o = 195 \text{ pF}$      | 956.2 kHz   | 1.087 MHz     |
|                         | $C_1 = 568.221 \text{ pF}$  |             |              |
|                         | $L_1 = 48.74 \mu \text{H}$  |             |              |
|                         | $R_1 = 3.5 \Omega$          |             |              |

Figure 3: Simulink model of equivalent circuit of piezoelectric element.
With change in pressure, the change in resonant frequency is 1.5 kHz. 1.5 kHz in 956 kHz is 0.16%. The resonant frequency is inversely proportional to the thickness of the piezoelectric disc [20]. As pressure is applied to the piezoelectric element, the thickness decreases and so there is an increase in the resonant frequency. As the pressure acting on the piezoelectric disc increases, the stiffness increases and so the resonant frequency increases. The values of resonant and anti-resonance frequencies obtained from the model response match with those obtained experimentally.

5. CONCLUSIONS
In this paper, a process condition based equivalent circuit model of piezoelectric disk is developed. The process conditions and their ranges considered are suitable for underwater applications. The temperature and pressure dependence of thickness mode resonant and anti-resonance frequency of the PZT 5 was found out experimentally. From these practically obtained values of the resonant and anti-resonant frequencies, the model parameters computed and an more realistic model was obtained. With increase in temperature decrease in the resonant and anti-resonant frequencies is observed. There is an increase in resonant frequency observed with increase in pressure. The values of resonant and anti-resonant frequencies of the model response match with the experimentally obtained values for given temperature and pressure conditions. This shows that the model parameters computed are accurate. This work can be further extended to compute other material constants which can be used to develop Finite element analysis based models of piezoelectric discs.
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