Performance Evaluation of Piezoceramic Sensors for Impact Detection

Piezoceramic Sensors for Impact Detection

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Abstract: This study presents a handy and low-cost method to examine the impact sensing properties of piezoceramics using a drop-weight impact approach and an IC-741 operational amplifier (OP-AMP) configured in astable mode. To illustrate, piezoelectric ceramics $Ba_{0.06}Na_{0.47}Bi_{0.47}TiO_3$ (BNBT) and $Ba_{0.85}Ca_{0.15}Zr_{0.10}Ti_{0.90}O_3$ (BCZT) have been considered in this work. The BNBT and BCZT ceramics were prepared through the conventional solid-state reaction method, and single-phase formation was verified via X-ray diffraction (XRD) analysis. XRD data, processed using FullProf software, provided insights into the crystal symmetry, space group, and lattice parameters of BNBT and BCZT. The surface morphology of both ceramics was studied by employing scanning electron microscopy (SEM). Results of the impact study for both materials showed that the dielectric constant and output waveforms increased proportionally with applied mechanical energy. Such a circuit offers potential applications in flow, pressure, and impact sensing. Further, the proposed experiment provides an important educational tool for undergraduate and postgraduate students in electrical engineering, materials science, and physics, or could be taken up as a project based on available experimental resources.

Keywords: *Ceramic; Lead Free; Piezoelectric; Dielectric; Impact Loading; Operational Amplifier.*

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I. INTRODUCTION

Piezoelectric sensing technology offers significant potential across diverse applications, including consumer electronics, pressure and acoustic sensors, biomedical instrumentation, automotive systems, environmental engineering, manufacturing processes, and many more. Ferroelectric materials are particularly advantageous for such applications due to their superior dielectric properties, which minimize operational noise, as well as their excellent piezoelectric response, which enhances sensing performance. However, commercially available sensing devices are often expensive and incorporate complex circuitry, thereby limiting their accessibility to many universities and institutions. Such complexity also makes it challenging for undergraduate (UG) and postgraduate (PG) students to fully understand their operation [1–3]. A thorough comprehension of circuit mechanisms, along with the dielectric and piezoelectric behaviour of materials, is therefore essential in fostering both conceptual and practical knowledge. Further, lead-free ferroelectric ceramics such as $Ba_{0.06}Na_{0.47}Bi_{0.47}TiO_3$ (BNBT) and $Ba_{0.85}Ca_{0.15}Zr_{0.10}Ti_{0.90}O_3$ (BCZT) have emerged as promising candidates for such studies owing to their outstanding dielectric and piezoelectric properties. In this work, we demonstrate a simple, low-cost impact-sensing experimental setup based on an astable (free-running) multivibrator constructed with an IC-741 operational amplifier (OP-AMP). The circuit, configured in free-running mode and coupled with a piezoelectric capacitor and a drop-ball impact mechanism, functions as a reliable impact-sensing device. This experiment not only provides UG and PG students with valuable hands-on experience in piezoelectric sensing and dielectric behaviour but also serves as an accessible educational tool that bridges theoretical knowledge with practical applications, especially in the fields of materials science and applied physics. The present study focuses on dielectric constant measurements using the IC-741 OP-AMP and investigates the influence of mechanical impacts on output pulse width. For this purpose, test capacitors fabricated from BNBT and BCZT piezo-ceramics were employed to assess circuit performance. Overall, the work introduces a practical, resource-aligned experimental model suitable for physics, materials science, and electrical engineering curricula, and highlights its potential as a cost-effective student project.

II. EXPERIMENTAL PROCEDURE

The piezo-ceramics chosen for this work are $Ba_{0.06}Na_{0.47}Bi_{0.47}TiO_3$ (BNBT) and $Ba_{0.85}Ca_{0.15}Zr_{0.10}Ti_{0.90}O_3$ (BCZT). These materials were synthesized using a standard high-temperature mixed oxide process with AR-grade (purity > 99.5%) carbonates and oxides in the correct stoichiometric ratios, under the optimized calcination and sintering conditions as detailed in earlier studies [4-7]. These ceramic powders were then compacted in a cylindrical die to form pellets of 10 mm diameter and ~1.5 mm thickness under a uniaxial pressure of 600 MPa using a hydraulic press. Polyvinyl alcohol (PVA) was incorporated as a binder. For fabricating the test capacitors used to measure the dielectric constant and output pulse width, silver paste (air-drying) was applied to both major faces of the polished sintered pellets, followed by firing at 500°C for 30 minutes to ensure the formation of firm electrodes and thereafter cooled to room temperature prior to conducting the experiments. X-ray diffraction (XRD) patterns of sintered BNBT and BCZT pellets were recorded at room temperature using a PANalytical XPERT-PRO diffractometer with CuKα radiation (λ = 1.5406Å) over a 2θ range of 20°–80°. Fractured surface micrographs of the BNBT and BCZT ceramics were captured using a JEOL JSM-7600F field emission scanning electron microscope (FESEM, Japan).

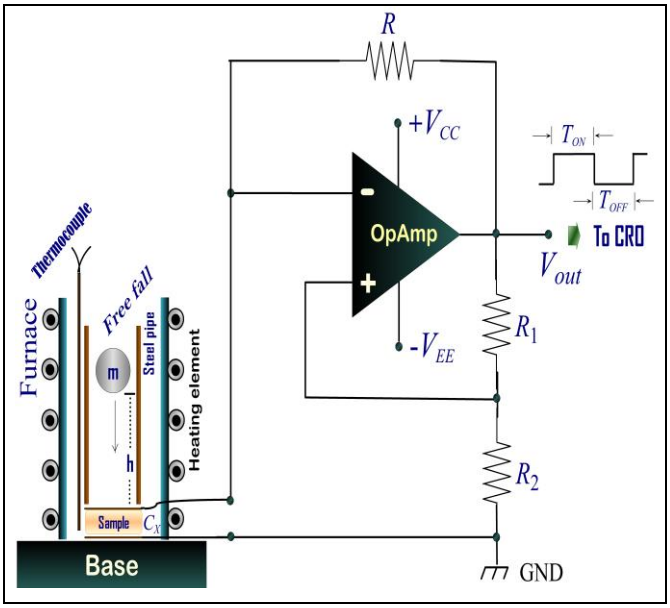

Fig 1 Astable Mode Connection Diagram Using IC-741 OP-AMP Along with Drop-Weight Impact Arrangement to Study the Impact Sensing Characteristics of BNBT and BCZT Ceramics.

Fig. 1 illustrates the connection diagram (external) of the IC-741 OP-AMP configured for an astable (free-running) operation, with two test capacitors composed of BNBT and BCZT ceramics (denoted as C_x) connected to a drop-ball setup. The circuit was fabricated on a logic breadboard centered around the IC-741. The output pulse width, indicative of the electrical response to mechanical impact, was obtained using a drop-weight impact technique at room temperature, observed on a cathode ray oscilloscope (CRO) screen connected to pin 6. The feedback resistors, R_1 and R_2, were set to equal values in this study. In order to realize the impact loading a steel ball (diameter = 2.33 cm and mass = 10 g) was allowed to drop from various heights ranging between 5 and 20 cm through a guiding steel pipe, imparting mechanical impact to the BNBT and BCZT test samples. The electrical responses of the BNBT and BCZT ceramic capacitors to the applied stress were monitored on a Rohde & Schwarz, Hameg (HMO 2524) make digital storage oscilloscope attached to a computer for data acquisition and analysis.

III. RELEVANT THEORY

The dielectric constant (ε) of a material can be calculated as [1]

$$\varepsilon = C_x / C_o \quad (1)$$

Where C_x and C_o (= $\varepsilon_o A/t$) are, respectively, the capacitance of the test capacitor and capacitance without dielectric having the same area (A) and thickness (t). Further, it is known that, unlike bistable or monostable multivibrators, the astable (free-running) multivibrator does not have any stable state. Instead, it continuously oscillates between two unstable states. However, the duration spent in each state is ascertained by the charging and discharging of a capacitor (C_x) through a resistor (R), as depicted in Fig. 1. Accordingly, the time period of oscillation at the output (pin 6) of the IC-741 operational amplifier operating in astable mode is given by [8]:

$$T = 2RC_x.\ln[(1+\beta)/(1-\beta)] \quad (2)$$

Here, the feedback fraction $\beta = R_2/(R_1+R_2)$. If we use both feedback resistors (R_1 and R_2) to be of the same value (*i.e.*, $R_1 = R_2 = R$), the value of β will be equal to 3. Therefore, equation (2) becomes,

$$T = 2RC_x.\ln 3 \quad (3)$$

Equation (3) dictates that when the resistance R is held constant, the width of the output pulse is governed by the value of the capacitor C_x only. Using equations (1) and (3), we can easily write:

$$\varepsilon = T / 2R.\ln 3.C_o \quad (4)$$

This expression indicates that the value of ε of a material is directly proportional to the astable output pulse width (T), i.e., $\varepsilon \propto T$. Hence, by substituting the experimentally measured value of T into equation (4), the value of the dielectric constant can easily be determined. Further, it is well known that piezoelectric materials can generate an electrical potential when subjected to mechanical stress. Besides, in an

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experiment investigating how mechanical impact influences the dielectric constant, suppose a linear relationship is observed, that is, an increase in mechanical energy ($E_m = mgh$) leads to an increase in the dielectric constant, and consequently, in T as well. Such a behavior is typically expressed by an equation of the form:

$$T = A + B.E_m \qquad (5)$$

Here, A and B are constant quantities. Utilizing equations (4) and (5), we can write

$$\varepsilon = (A + B.E_m)\ /2R.\ln 3.C_o \qquad (6)$$

Therefore, this expression provides the values of the dielectric constant as a function of applied impact for the experimental arrangement under consideration (Fig. 1).

IV. RESULTS AND DISCUSSION

Fig. 2 presents the indexed XRD patterns for the sintered BNBT and BCZT ceramics. The BNBT ceramic was structurally refined with FullProf software, identifying a rhombohedral-tetragonal structure using the $R3c$ (161) space group. The refined lattice parameters for BNBT are $a = b$ = 3.9037 Å, c = 3.898 Å, with c/a = 0.998, and a unit cell volume of 58.86 Å^3, consistent with previous studies [4,5,9,10]. Besides, the XRD analysis of BCZT ceramic revealed a tetragonal structure with unit cell parameters: $a = b$ = 2.8247 Å and c = 3.9945 Å, in the space group: $P4/mmm$ (123), aligning with earlier reports [6,7,11].

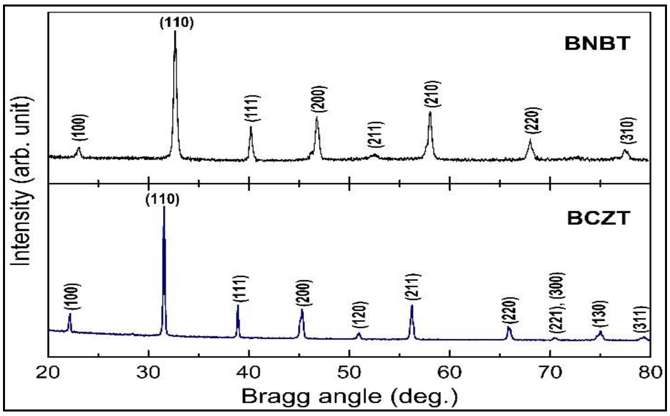

Fig 2 Indexed XRD Patterns of Sintered BNBT and BCZT Ceramics at Room Temperature.

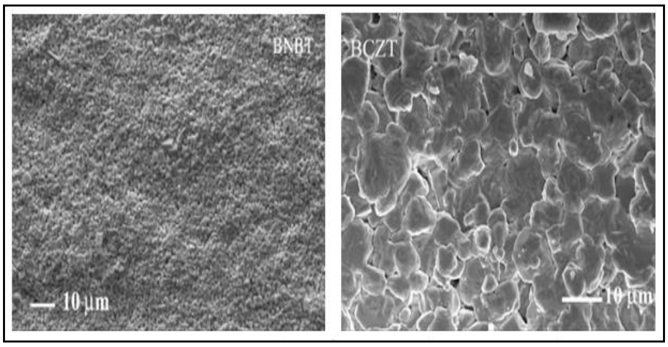

Fig 3 SEM Micrographs of Sintered BNBT and BCZT Ceramics at Room Temperature.

The microstructure, captured by scanning electron microscopy (SEM) and displayed in Fig. 3, shows a dense structure with minimal voids, indicating high specimen density. The average grain sizes were approximately 3 µm and 7 µm for BNBT and BCZT, respectively. These findings confirm the fabrication of single-phase BNBT and BCZT ceramic samples.

Figs. 4(a), 4(b), 5(a), and 5(b) illustrate the variation of the time period (T) and dielectric constant (ε) as a function of applied mechanical energy (E_m) at room temperature, together with the fitted trend lines corresponding to BNBT and BCZT ceramics. The results indicate that the output pulse width, measured at pin 6 of the circuit, increases with E_m for both BNBT and BCZT ceramics. This behaviour highlights the direct influence of mechanical impact on the dielectric response of the ferroelectric ceramics under investigation. Both BNBT and BCZT are believed to be the representative lead-free ferroelectric compounds with non-centrosymmetric perovskite (ABO_3 type) crystal structures.

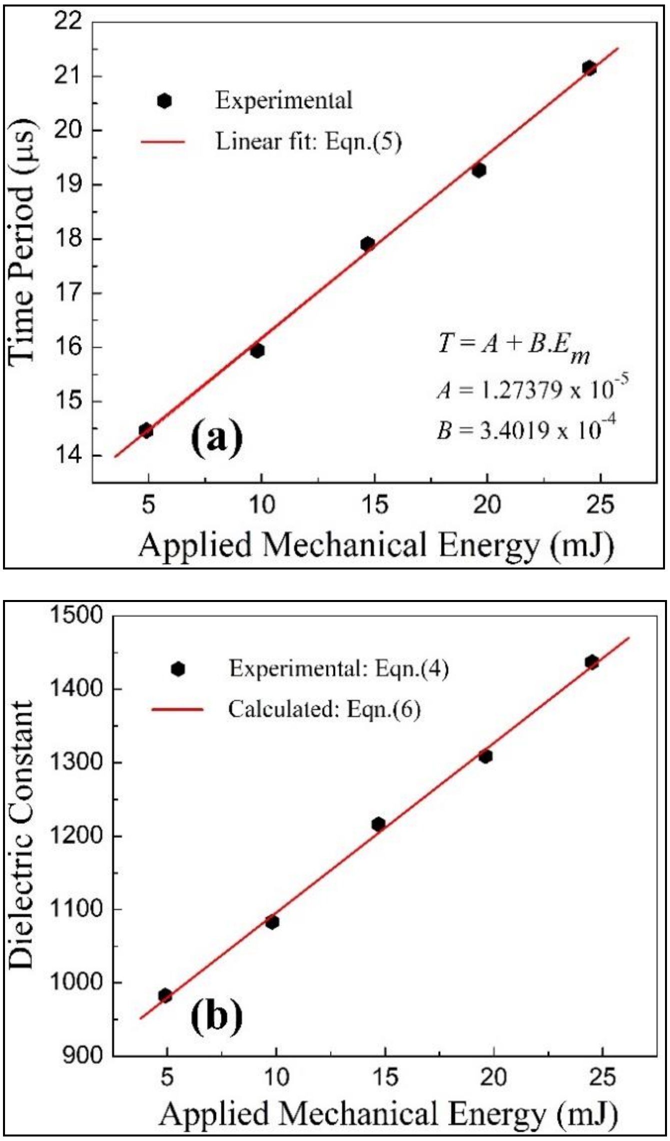

Fig 4 Variation (Experimentally Observed and Fitted Curve) of (a) Time Period (T) and (b) Dielectric Constant (ε) of BNBT Ceramic with Applied Mechanical Energy.

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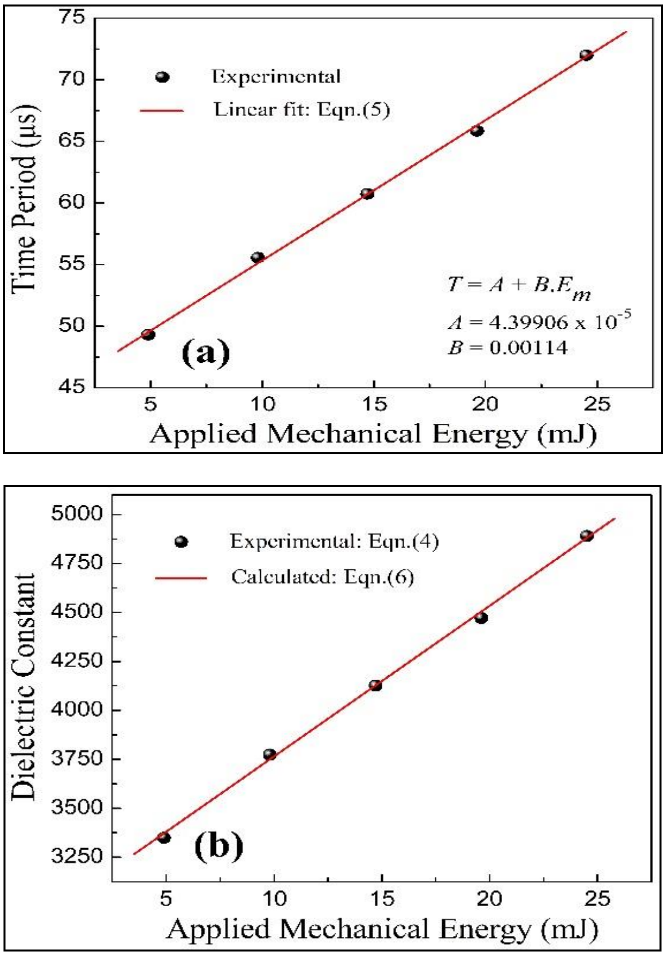

Fig 5 Variation (Experimentally Observed and Fitted Curve) of (a) Time Period (T) and (b) Dielectric Constant (ε) of BNBT Ceramic with Applied Mechanical Energy.

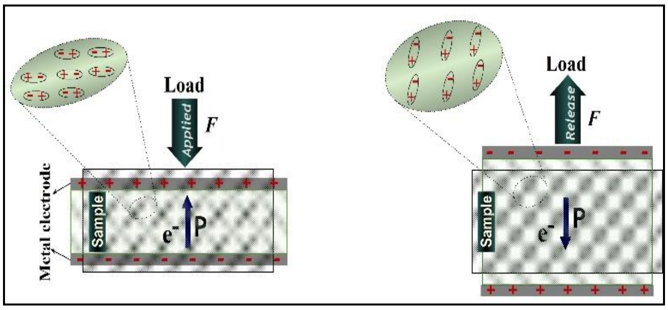

Fig 6 Schematic Diagram of Ceramic Material Illustrating Change in Dimension Leading to the Change in Total Polarization Under Drop Weight Impact Method.

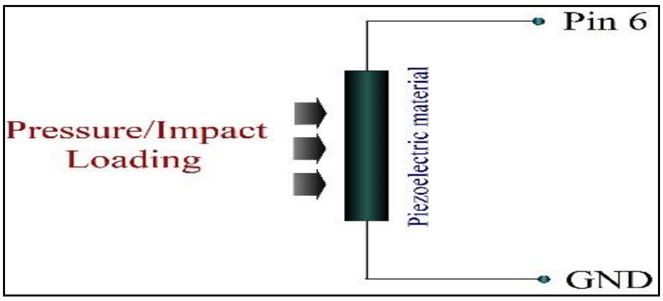

Fig 7 Schematic Diagram for the Implementation of Impact (or Pressure) Sensing Along with the Respective Pin Numbers.

This behaviour highlights the direct influence of mechanical impact on the dielectric response of the ferroelectric ceramics under investigation. Both BNBT and BCZT are believed to be the representative lead-free ferroelectric compounds with non-centrosymmetric perovskite (ABO_3 type) crystal structures. Their fundamental structural units consist of TiO_6 and/or ZrO_6 octahedra, which host polarizable electric dipoles (Ti–O and Zr–O electric dipoles). Upon the application of external mechanical impact, the physical dimensions of the ceramic samples undergo slight modifications, leading to distortions of these octahedra. Such distortions alter the relative positions of the constituent dipoles and modify their separation distance. As a result, the dipoles tend to reorient along the direction of the applied impact, giving rise to a net shift in the overall polarization of the material. This polarization change, in turn, directly influences the effective capacitance of the system, and consequently the dielectric constant (ε), as schematically represented in Fig. 5. Since the time period of oscillation T is directly proportional to the capacitance C_x (as established in Eq. 3), the dielectric response of the materials to applied mechanical energy follows the same systematic trend. This proportionality is clearly reflected in Fig. 3(b), where ε exhibits a consistent increase with impact energy. The observed results are in good agreement with previously reported studies on similar systems subjected to external mechanical loading [6,12,13], thereby validating the reliability of the present experimental approach. It is seen that within the studied energy range, both BNBT and BCZT ceramics exhibit a nearly linear dependence of dielectric constant on applied mechanical energy. Such a linear and reproducible response is of significant importance, as it indicates that the present circuit configuration can serve as a practical piezo-sensing device. Specifically, the simplicity and low cost of the design make it suitable for applications in impact sensing or flow sensing technologies. A schematic illustration of the potential utilization of the circuit in such applications is provided in Fig. 6. Thus, the present results not only shed light on the electromechanical coupling mechanisms in BNBT and BCZT ceramics but also demonstrate their feasibility for integration into cost-effective sensing systems.

V. CONCLUSIONS

This study introduces a simple and low-cost method for investigating the impact-sensing behaviour of piezoceramics using a drop-weight approach in combination with an IC-741 operational amplifier (OP-AMP) configured in astable mode. Lead-free ceramics, $Ba_{0.06}Na_{0.47}Bi_{0.47}TiO_3$ (BNBT) and $Ba_{0.85}Ca_{0.15}Zr_{0.10}Ti_{0.90}O_3$ (BCZT), were synthesized via the conventional solid-state route, and phase purity was confirmed through X-ray diffraction (XRD) with FullProf refinement, while scanning electron microscopy (SEM) provided insights into their surface morphology. Impact studies revealed a proportional increase in both dielectric constant (ε) and output waveform characteristics with applied mechanical energy, reflecting the strong electromechanical coupling in BNBT and BCZT. These results demonstrate the suitability of the proposed circuit for low-cost sensing applications such as flow, pressure, and impact detection.

Also, beyond its functional value, the experimental setup offers significant educational utility. Its straightforward design enables easy implementation in undergraduate and postgraduate laboratories, where students can directly explore fundamental concepts of piezoelectricity, dielectric behaviour, and circuit operation. Such hands-on exposure bridges theoretical learning with experimental practice and provides a strong foundation for further research. Besides, the versatility of the setup also permits adaptation for studying dielectric responses under alternative external stimuli, such as temperature or electric field. In the future, ceramic/polymer or ceramic/rubber composites may be used to make the system more adaptable for different applications. Overall, this work shows the scientific value and educational usefulness of the low-cost setup, which can support both research and teaching in materials science, applied physics, and electrical engineering.

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