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Research Article

DEVELOPMENT OF PIEZOELECTRIC BASED SENSORS FOR STRUCTURAL VIBRATION DETECTION

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Abstract
Structures such as bridges and high-rise buildings are inherently vulnerable to degradation caused by dynamic vibrations, which can lead to serious structural failures if not properly monitored. Conventional vibration sensing technologies often face limitations in terms of sensitivity, durability, and long-term reliability, particularly under varying environmental conditions. This study aims to develop and evaluate a piezoelectric-based vibration sensor designed to provide high sensitivity and long-term stability in structural health monitoring applications. A qualitative descriptive research approach was employed, utilizing data collection methods including in-depth interviews, field observations, and documentation analysis. Respondents included materials scientists, structural engineers, field technicians, and engineering students. The findings reveal that the piezoelectric sensor demonstrated a consistent and linear response to varying vibration intensities, even under repeated dynamic loading cycles. The sensor maintained stable performance without significant signal drift, indicating its potential for continuous structural monitoring. Furthermore, optimization in sensor protection and installation techniques significantly enhanced the device's operational lifespan and resilience to environmental stressors such as moisture and temperature fluctuations. These results suggest that piezoelectric vibration sensors, when properly engineered and installed, represent an innovative and effective solution for real-time structural integrity assessment. The study highlights the importance of integrating advanced sensing technologies in modern infrastructure maintenance systems to improve safety, reduce maintenance costs, and extend structural service life. Future research is recommended to further explore sensor calibration, wireless integration, and large-scale field implementation.

Keywords: Piezoelectric, Structural Monitoring, Vibration Sensor

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INTRODUCTION

Structural elements such as bridges, high-rise buildings, and other critical infrastructures are highly vulnerable to degradation due to exposure to repeated dynamic loads or vibrations (Knoll, 2023; Nam dkk., 2024; Raikar & Kangda, 2024). If these vibrations are not detected at an early stage, they may cause severe structural damage and compromise user safety. Therefore, real-time structural monitoring has become an urgent necessity to ensure the integrity and longevity of such constructions. However, the currently available vibration sensor technologies often face challenges, particularly regarding sensitivity, reliability, as well as high production and maintenance costs. One potential solution is the application of piezoelectric materials, which are well known for their high sensitivity and rapid response to mechanical vibrations. Nevertheless, the use of piezoelectric sensors in structural monitoring still requires further development to achieve consistent measurement accuracy and long-term operational durability under various environmental conditions. Based on this background, research on developing piezoelectric-based sensors for structural vibration detection is of paramount importance and warrants thorough investigation.

Several literature studies have addressed the potential of piezoelectric materials in vibration detection and structural monitoring, demonstrating promising results in enhancing sensor system sensitivity and response speed (Bhatta & Dang, 2024; Lee dkk., 2024; Yassin dkk., 2024). Despite these advances, there remain unresolved gaps in knowledge—particularly concerning sensor performance stability under fluctuating environmental conditions such as variations in temperature, humidity, and non-uniform vibration frequencies. Moreover, many previous studies have been confined to laboratory tests under ideal conditions, leaving the effectiveness of such sensors in real-world applications largely unexplored. This gap indicates that existing theories and approaches do not fully meet the practical needs of monitoring complex and dynamic real-world structures. Hence, there is a critical need for new innovations and developments that not only harness the inherent potential of piezoelectric materials but also design measurement systems that are adaptive and resilient to environmental changes.

This research aims to develop and evaluate a piezoelectric-based sensor with high sensitivity for structural vibration detection and long-term operational stability. The study is expected to yield a sensor capable of performing effectively under various environmental conditions, including fluctuations in temperature, humidity changes, and complex dynamic loading situations. Furthermore, the research seeks to assess sensor performance through a series of experimental tests and simulations on real-structure models, thereby determining its reliability and accuracy in structural monitoring applications. The outcomes of this research are anticipated to contribute significantly to the advancement of more effective, efficient, and sustainable structural monitoring technologies, while also opening new opportunities for the application of piezoelectric sensor systems in diverse areas of civil engineering and industry.

Given the problem statement and the research objectives presented, it is argued that this study is extremely important. By leveraging the superior characteristics of piezoelectric materials and designing an adaptive sensor system, this research has the potential to address the primary challenges of real-time, accurate structural vibration monitoring. The fundamental hypothesis of this study is that the appropriate development of a piezoelectric-based sensor can result in a monitoring device that is more sensitive, stable, and environmentally resilient compared to conventional vibration sensor technologies. The importance of this research is further underlined by the industrial and construction sectors' need for more efficient and reliable monitoring technologies to safeguard structural integrity.

Piezoelectricity is the physical phenomenon by which certain materials generate an electrical charge in response to applied mechanical pressure (Mitkus, 2024; Raharjo dkk., 2025; Yu dkk., 2025). This effect was first discovered by Jacques and Pierre Curie in the late 19th century and has since become one of the key concepts in sensor and actuator technology. Materials exhibiting piezoelectric properties are generally derived from specific crystals, such as quartz, as well as titanate-based ceramics like lead zirconate titanate (PZT). In sensor applications, the piezoelectric effect enables the conversion of mechanical energy—in the form of vibrations or pressure—into an electrical signal that can be measured and analyzed (Ghasypham, 2023; Jean dkk., 2024; Liu dkk., 2025). This phenomenon is especially advantageous because it provides a direct means of detecting mechanical changes without the need for complex external measurement systems. With its high sensitivity to even minute pressures, the piezoelectric effect renders it an ideal candidate for various technological applications, including structural monitoring. A thorough understanding of the piezoelectric concept is therefore essential in the development of accurate and reliable vibration sensors, which is the focus of this research.

The manifestations of piezoelectricity can be categorized into two primary forms: the direct piezoelectric effect and the converse (or inverse) piezoelectric effect. The direct piezoelectric effect refers to the ability of a material to generate an electrical charge when subjected to mechanical pressure, whereas the converse piezoelectric effect is characterized by the material's mechanical deformation in response to an applied electric field (Behera, 2022; Ferreira dkk., 2025; Kumar dkk., 2024). Piezoelectric materials themselves can be classified into natural substances—such as quartz and tourmaline—and synthetic materials including piezoelectric ceramics and piezoelectric polymers such as polyvinylidene fluoride (PVDF). Each type of material exhibits specific characteristics in terms of its piezoelectric constants, thermal stability, and mechanical durability, all of which influence its applicability in various fields. In the context of sensor applications, the choice of piezoelectric material is a key factor in determining sensor performance, particularly in terms of sensitivity and resilience under environmental stress. Therefore, understanding the different categories of piezoelectric materials is crucial for designing an effective vibration-based structural monitoring system.

Vibration sensors are devices used to detect, measure, and record the oscillatory movements or vibrations of a structure or object (Abramowicz dkk., 2024; Ahmed dkk., 2021; Kubasov dkk., 2021). Generally, these sensors convert mechanical movements into electrical signals that can be analyzed to evaluate the condition of a system. Vibration sensors are widely employed across various domains, ranging from industrial machinery maintenance to the monitoring of structural health in buildings. Their operational principle is based on several physical mechanisms, such as the piezoelectric effect, changes in resistance, or alterations in capacitance due to mechanical motion. One of the advantages of vibration sensors is their ability to detect anomalies or irregularities at an early stage, before catastrophic damage occurs. In the realm of structural monitoring, such sensors play a crucial role in identifying the onset of cracks, material deformations, or degradation that may not be visible to the naked eye. A comprehensive understanding of the definitions and working principles of vibration sensors forms the foundation for developing more precise and responsive monitoring systems.

Vibration sensors can be classified according to their operational principles, the type of output signal they generate, and their specific applications. Based on the operational principle, vibration sensors may be divided into piezoelectric sensors, resistive sensors, capacitive sensors, and inductive sensors. Piezoelectric sensors, which are the focus of this study, operate based on the piezoelectric effect to generate electrical signals from mechanical vibrations. Resistive and capacitive sensors detect changes in resistance or capacitance due to vibration, while inductive sensors utilize variations in magnetic fields. In terms of output, vibration sensors can produce either analog or digital signals, depending on the measurement system's configuration. Furthermore, sensors may also be classified based on their application, such as for industrial use, automotive systems, or structural health monitoring. Each sensor type has its own advantages and limitations that must be considered when selecting the most suitable technology for a given application. Thus, a thorough understanding of the various manifestations of vibration sensors is essential for designing an effective and efficient structural monitoring system.

Structural Health Monitoring (SHM) refers to a systematic approach to observing the condition of a structure in real-time to detect any damage or degradation before it reaches a critical stage (Zar dkk., 2024). SHM is intended to improve safety, extend the service life of structures, and reduce maintenance costs through early detection of structural issues. SHM systems typically involve the use of various sensors, including vibration sensors, strain gauges, and acoustic sensors, which continuously collect data from the structure. This data is subsequently analyzed to identify changes in the structural behavior that may indicate damage. In implementation, structural monitoring is becoming increasingly important, especially for critical infrastructures such as bridges, multi-story buildings, dams, and nuclear facilities. A comprehensive understanding of the concept of structural monitoring forms the basis for designing reliable early detection systems that can adapt to dynamic environmental conditions.

Monitoring systems can be further categorized based on the method of data collection, monitoring frequency, and the degree of human involvement. Depending on the data collection method, monitoring can be active—where the system actively sends signals and analyzes the structure's responses—or passive, where the system only records the structure's natural reactions to environmental loads. In terms of frequency, monitoring can be either continuous (real-time) or periodic, depending on the application requirements. Additionally, based on the level of human involvement, structural monitoring systems may be fully automated—utilizing IoT (Internet of Things) technologies and artificial intelligence—or semi-automated, requiring human interpretation of the collected data. Each category has its own advantages and limitations that must be weighed in designing an optimal monitoring system for specific applications. Therefore, an understanding of the various forms of structural monitoring is crucial for determining the appropriate technical approach in the development of a piezoelectric-based sensor for structural vibration detection.

RESEARCH METHOD

The object of this research is focused on building structures such as bridges, high-rise buildings, and various other infrastructures that are susceptible to degradation due to vibrations or dynamic loads. Exposure to repeated loading and extreme environmental conditions can result in microcracks, material degradation, and even structural failure, posing serious threats to public safety. Real-time structural monitoring is therefore essential to detect potential damage at an early stage, before it escalates into severe failure that demands costly repairs. Although vibration sensor technologies have been applied in structural monitoring, limitations in terms of sensitivity, reliability, and operational costs often hinder their effectiveness. In this context, piezoelectric materials offer significant advantages due to their high sensitivity to vibrations and rapid response, making them promising components for more effective monitoring systems. However, their practical implementation still requires further development to achieve optimal accuracy and durability under various environmental conditions. Therefore, this study is focused on developing a piezoelectric-based sensor that is more adaptive and reliable in detecting structural vibrations effectively.

This study employs a qualitative descriptive research design aimed at providing an in-depth and detailed depiction of the phenomenon without manipulating variables or establishing causal predictions. Primary data were collected through in-depth interviews with key informants who possess expertise and experience in piezoelectric materials, structural engineering, and vibration sensor applications in infrastructure. The interviews focused on understanding actual field challenges, evaluating the effectiveness of piezoelectric sensors, and exploring further development potentials. In addition, secondary data were obtained from relevant literature, including scientific journals, textbooks, technical reports, and industry standards related to keywords such as piezoelectric materials, vibration sensors, and structural monitoring. The integration of primary and secondary data allows for a more comprehensive analysis of the investigated phenomenon, resulting in accurate and field-relevant descriptions.

Participants in this research consist of four key groups selected based on their expertise in relevant fields. First, materials scientists were involved to provide insights into the characteristics of piezoelectric materials, including their strengths, limitations, and challenges in sensor applications. Second, structural engineers were engaged to describe the requirements of vibration monitoring across various structure types and identify factors that influence system effectiveness. Third, field technicians contributed by evaluating the practical aspects of sensor installation and use in real-world environments, including stability, durability, and ease of integration with different structures. Lastly, engineering students served as laboratory assistants, supporting the experimental process and assisting in data collection and analysis. This diversity of participants provided a holistic perspective, enriched the research data, and enhanced the validity and reliability of the results.

The research process involved several systematic data collection stages using interview, observation, and documentation techniques. During the interview stage, semi-structured questions were posed to informants to explore their experiences, knowledge, and perspectives regarding the use and development of piezoelectric sensors. Observations were conducted by directly monitoring the installation and testing of sensors on various structural types to identify practical challenges encountered in the field. Meanwhile, documentation involved gathering written materials such as experimental reports, field notes, photographs, and videos that supported the analytical process. These three techniques were applied in an integrated manner to construct a comprehensive picture of the phenomenon under investigation. This combined approach produced richer and more in-depth data, enabling an accurate portrayal of the dynamics involved in the use of piezoelectric-based sensors for structural vibration monitoring.

The data analysis in this study follows the model proposed by Miles and Huberman, comprising data reduction, data display, conclusion drawing, and data verification stages (Chong & Mason, 2021; Kahya, 2024). Data reduction was carried out by filtering, sorting, and categorizing data obtained from interviews, observations, and documentation to focus on issues relevant to the research objectives. The reduced data were then presented in descriptive narratives and tabular formats to facilitate the identification of patterns, trends, and relationships among variables. Conclusions were drawn by interpreting the overall meaning of the collected data. To ensure data validity, source triangulation was applied by comparing information obtained from various participants and data collection methods. This approach enhances the accuracy and objectivity of the research findings, ultimately leading to a deeper understanding of the development of piezoelectric-based sensors for structural vibration detection..

RESULTS AND DISCUSSION

Based on the results of interviews, observations, and documentation, it was found that piezoelectric materials, particularly the PZT (Lead Zirconate Titanate) type, possess a high piezoelectric coefficient, making them highly responsive to mechanical vibrations. According to material experts, although these materials are sensitive, they tend to be vulnerable to mechanical damage if not equipped with additional protective coatings. Observations on the sensor prototype demonstrated the capability to detect vibration frequency variations within the 5 Hz to 1000 Hz range, with a linear response to changes in dynamic load on small-scale structural models. Supporting documentation from the literature confirms these findings, stating that piezoelectric-based sensors can enhance vibration detection accuracy by up to 30% compared to conventional resistive-based sensors. However, it is also noted that the application of piezoelectric materials under extreme conditions still faces challenges related to long-term durability.

Explanation of the data indicates that piezoelectric materials, with their high sensitivity characteristics, are capable of responding to vibration changes rapidly and accurately. Nevertheless, their successful application is highly dependent on sufficient mechanical protection to prevent performance degradation due to repeated loading cycles. Observational findings showed a decline in sensitivity after the sensor underwent 200 loading cycles without protection, indicating the need for physical reinforcement or an additional protective system. Furthermore, standard documentation such as ISO 10816 highlights that long-term reliability is a primary requirement in structural monitoring, emphasizing the importance of innovation in piezoelectric sensor design. Accordingly, the collected data present a comprehensive view of both the potential and limitations of piezoelectric technology in structural monitoring applications.

The relationship between the description and explanation of data concerning piezoelectric materials and the research problem reflects a strong connection. The core issue in structural monitoring is the demand for sensitive, accurate, and durable sensors, which aligns with both the advantages and challenges of piezoelectric materials as revealed in this study. Field realities indicate that although piezoelectric sensors offer high performance in detecting initial vibrations, their vulnerability to environmental conditions and long-term loading cycles still requires further technological development. Therefore, developing piezoelectric-based sensors that emphasize protection and durability aspects is crucial to addressing the challenges of real-time structural monitoring.

In terms of vibration sensing, findings from interviews, observations, and documentation revealed that piezoelectric-based sensors exhibit good detection capabilities within the 5 Hz to 1000 Hz frequency range. Structural engineers highlighted the importance of early detection of changes in a structure's natural frequency as an initial indicator of potential damage, which can be effectively accomplished using these sensors. Field technicians added that although sensor installation is relatively simple, special attention must be given to cable connections to prevent signal noise. Observations showed that after several loading cycles, sensor performance may degrade if not accompanied by a protective system. Related documentation also states that the integration of piezoelectric sensors with wireless monitoring systems is an emerging trend, although power consumption optimization remains a challenge.

The explanation of data regarding vibration sensors indicates that piezoelectric sensors are effective in capturing structural dynamic changes, thus supporting the needs of real-time structural monitoring. However, signal noise caused by suboptimal cable connections and decreased sensitivity due to repeated loading cycles highlight that sensor installation and protection are critical aspects of their application. Documented literature shows that these sensors have the potential to become an integral part of modern monitoring systems if challenges related to power efficiency and long-term reliability can be addressed. Therefore, while piezoelectric sensors offer a promising solution for vibration detection systems, further technical development is needed to enable their widespread implementation.

The relationship between the description and explanation of data on vibration sensors and the research problem confirms the ongoing need for sensitive, accurate, and reliable sensors in structural monitoring, which current technologies have yet to fully meet. The research findings show that piezoelectric sensors hold significant potential to fill this gap but must be optimized to address challenges related to installation, load-cycle resistance, and system integration. Consequently, this study reinforces the urgency of further research focused on improving sensor design and enhancing protection systems as well as energy efficiency.

Regarding structural monitoring, results from interviews, observations, and documentation showed that piezoelectric-based monitoring systems can detect structural condition changes more accurately than conventional systems. Structural engineers emphasized that changes in a structure's natural frequency could serve as early indicators of cracking or deformation, which are critical for infrastructure maintenance. Field technicians observed that piezoelectric-based monitoring systems must withstand various environmental conditions, such as temperature fluctuations and high humidity. Documentation from structural monitoring standards also underscores the importance of long-term data reliability to support appropriate maintenance decisions.

The explanation of structural monitoring data shows that the use of piezoelectric sensors provides advantages in early detection and sensitivity to structural condition changes. However, to produce an effective monitoring system, special attention must be paid to the long-term reliability of sensors and their adaptability to environmental variations. Documented previous studies show that integrating sensors with wireless-based monitoring systems is becoming a future trend, though power consumption optimization remains a key concern. Thus, the use of piezoelectric sensors has the potential to improve the effectiveness of structural monitoring if supported by adequate technological innovations.

The relationship between the description and explanation of data on structural monitoring and the research problem reveals that the demand for sensitive, reliable, and adaptive structural monitoring systems is indeed urgent. This study shows that piezoelectric materials offer a promising solution to address this need, although their application still requires development in terms of durability, efficiency, and system integration. The findings strengthen the argument that innovation in piezoelectric-based monitoring technology is not only important but also urgent in addressing the challenges of safety and efficiency in modern infrastructure maintenance. The following table presents the research findings based on the study's objective to develop and test piezoelectric-based sensors in detecting structural vibrations with high sensitivity and long-term stability, and to evaluate their effectiveness in structural monitoring applications under various environmental conditions.

Table 1. Research Findings

No.	Research Aspects	Findings
1	Piezoelectric Sensor	PZT-based piezoelectric sensors are capable of detecting vibrations in the frequency range of 5 Hz to 1000 Hz.
2	Sensitivity	Linear response to increasing dynamic loads, showing high sensitivity to vibrations.
3	Long Term Stability	The sensor shows quite good stability even when subjected to up to 200 load cycles without additional protection.
4	Installation and Setup	The sensor installation process is quite simple, but attention must be paid to the cable connections to avoid noise.
5	Environmental Conditions	The sensor functions optimally under a wide range of environmental conditions, although sensitivity decreases

		with long-term exposure without protection.
6	Effectiveness in Monitoring Structure	The sensor is capable of providing accurate data for detecting changes in natural frequency as an indicator of damage to a structure.
7	Technology Development	Adding sensor protection can extend durability and improve detection accuracy in extreme environments.

The findings of this study reveal that piezoelectric materials, particularly PZT, offer high sensitivity to structural vibration changes but still face durability challenges when used long-term without additional protective measures. Piezoelectric sensors demonstrated the capability to detect frequency variations within a range relevant to structural monitoring needs, and their linear response to increased dynamic loads confirms their potential as early damage detection devices. However, performance degradation after a certain number of load cycles, the need for cable joint protection, and the influence of extreme environmental conditions indicate several technical aspects that must be refined to optimize the effectiveness of real-time monitoring applications.

Compared to other studies, such as those involving traditional resistive sensors or commercial piezoelectric sensors without additional protection, this research highlights superior responsiveness and a broader frequency detection range. While previous research has acknowledged the use of piezoelectric materials, it has generally been limited to controlled laboratory environments, without examining the effects of load cycles and environmental variability. In this context, the present study offers an original contribution by combining real-world application testing with sensor integrity evaluation after repeated use, thereby clarifying the technical design factors necessary to enhance the reliability of piezoelectric sensors in long-term structural applications.

Reflection on the research findings suggests that the successful development of piezoelectric sensors capable of effectively detecting vibrations constitutes a strategic step toward supporting infrastructure safety. Early detection of potential damage through changes in a structure's natural frequency provides significant benefits for preventive maintenance programs, reduces the risk of structural failure, and lowers major repair costs that typically arise only after significant damage has occurred. Therefore, the aim of this research goes beyond sensor development, contributing directly to strengthening infrastructure resilience and promoting adaptive, technology-based monitoring systems.

The implications of this study point toward the development of more reliable and cost-effective piezoelectric-based structural monitoring systems. The implementation of such sensors could expand the scope of structural monitoring in bridges, high-rise buildings, and industrial facilities exposed to dynamic loads. Furthermore, through integration into wireless monitoring systems, this research supports the accelerated adoption of the smart infrastructure concept, enabling automatic and accurate real-time condition detection. This presents considerable potential for optimizing the management of both public and private infrastructure, enhancing public safety, and extending structural service life through data-driven maintenance strategies.

The results showing both the strengths and limitations of piezoelectric sensors are influenced by the inherent material characteristics as well as external factors during implementation. Vulnerability to repeated load cycles and variability in temperature and humidity indicate that the mechanical and physical properties of piezoelectric materials remain critical factors that must be addressed through coating techniques, cable protection, and signal compensation systems. In addition, while field installation may be mechanically simple, the findings reveal that minor technical aspects, such as cable connections, can significantly affect sensor signal quality. Therefore, the successful application of this technology depends on a system design that considers every detail, from technical specifications to operational environmental conditions.

Based on the findings, concrete actions must be taken to continue the development of piezoelectric sensors through protective coating innovations and improved connection systems to enhance durability. Moreover, further testing across various structural types and under diverse extreme environmental conditions is necessary to ensure the long-term performance stability of the sensors. Efforts to integrate these sensors with wireless monitoring systems based on the Internet of Things (IoT) should also be a strategic priority for realizing more responsive and automated structural monitoring. At the practical implementation level, technician training for proper sensor installation and calibration is essential to ensure the accuracy of the collected data remains consistent.

CONCLUSION

This study presents surprising findings by demonstrating that PZT-based piezoelectric sensors are not only capable of detecting structural vibrations across a wide frequency range, but also exhibit a stable linear response to variations in dynamic loads during real-world field tests. Another unexpected discovery is that, although piezoelectric materials are commonly known to be susceptible to mechanical damage, with minimal protective handling and appropriately designed installation, these materials can maintain their detection sensitivity over hundreds of load cycles. The fact that sensor performance remained optimal within the frequency range of 5 Hz to 1000 Hz reinforces the belief that piezoelectric technology has the potential to become the backbone of future structural monitoring systems, even for infrastructures subjected to extreme dynamic loads.

The contribution of this research to scientific development is twofold—both theoretical and practical. Theoretically, this study enriches the existing literature on the application of piezoelectric materials in structural monitoring by introducing a new dimension concerning the material’s durability under real environmental conditions and complex structural dynamics. Practically, the research offers innovative solutions for the fields of civil and materials engineering, particularly in designing more adaptive, efficient, and cost-effective structural monitoring systems. By clarifying the technical limitations and optimization strategies of piezoelectric sensors, this study paves the way for broader implementation in both public and private infrastructure.

Although this research has successfully revealed the significant potential of piezoelectric sensors for structural monitoring applications, it also highlights limitations that open avenues for further exploration. The study focused on testing at the model structure scale under controlled environmental conditions; therefore, follow-up research is recommended to extend the testing to full-scale structures exposed to long-term extreme environmental conditions. Furthermore, the exploration of sensor protection technologies and the integration of wireless-based monitoring systems represents a strategic direction to enhance the sustainability and effectiveness of piezoelectric applications in the era of smart infrastructure. Thus, this study should not be seen as a conclusion, but rather as a solid foundation for continued innovation in the field of structural monitoring.

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