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Comparative Analysis of PZT, AlN, and PVDF Piezoelectric Materials for Vibrational Energy Harvesting: A Parameter-Focused Study

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Abstract: Piezoelectric energy harvesting has garnered significant interest as a sustainable method for generating electrical power from mechanical vibrations. In this study, we compare the performance of three commonly used piezoelectric materials—Lead Zirconate Titanate (PZT), Aluminum Nitride (AlN), and Polyvinylidene Fluoride (PVDF)—for vibrational energy harvesting applications. Using computational simulations, we analyze the average harvested power, peak power, power density, and power-to-acceleration ratio for varying thicknesses of each material. Our results reveal distinct performance characteristics among the materials, with PZT exhibiting superior power output and efficiency compared to AlN and PVDF. AlN demonstrates moderate performance across the parameters studied, while PVDF exhibits comparatively lower power output and efficiency. These findings provide valuable insights for engineers and researchers in selecting the most suitable piezoelectric material for energy harvesting applications based on specific performance requirements and constraints.

Keywords: Energy, Power, Harvesting, PZT, PVDF, AlN.

I. INTRODUCTION

In the wake of escalating energy demands and environmental concerns, the exploration of renewable and sustainable energy sources has become imperative. Energy harvesting technologies offer a promising avenue to address these challenges by capturing and converting ambient energy from various sources into usable electrical power. Among these technologies, MEMS (Micro-Electro-Mechanical Systems) piezoelectric vibrational energy harvesting has emerged as a promising solution. By harnessing mechanical vibrations from the surrounding environment, MEMS piezoelectric energy harvesters have the potential to provide a renewable and eco-friendly source of electricity for small-scale electronic devices and wireless sensor networks. At the core of MEMS piezoelectric vibrational energy harvesting lies the principle of piezoelectricity. Piezoelectric materials, such as certain ceramics and crystals, possess the unique ability to generate electric charge in response to mechanical stress or deformation. In MEMS energy harvesters, piezoelectric elements are integrated into micro-scale structures, allowing them to efficiently convert mechanical vibrations into electrical energy [1-4]. These devices typically consist of a cantilever or membrane structure, with piezoelectric layers sandwiched between electrodes. When subjected to mechanical vibrations, the piezoelectric material experiences strain, leading to the generation of electric charges that can be harvested and stored for powering electronic devices. MEMS piezoelectric vibrational energy harvesters offer several advantages that make them attractive for various applications. Firstly, their compact size and lightweight nature make them well-suited for integration into small-scale electronic devices and wireless sensor networks, where space and weight constraints are critical. Additionally, MEMS fabrication techniques enable the mass production of energy harvesters at a low cost, facilitating their widespread deployment in diverse environments.

Furthermore, MEMS piezoelectric harvesters exhibit high efficiency in converting mechanical vibrations into electrical energy, maximizing energy harvesting capabilities and enhancing overall system performance. The versatility of MEMS piezoelectric vibrational energy harvesting enables its application across a wide range of industries and sectors. In structural health monitoring, MEMS energy harvesters can be integrated into bridges, buildings, and infrastructure to power wireless sensor networks for real-time monitoring of structural integrity and health. Similarly, in the automotive sector, MEMS energy harvesters can harness vibrations from vehicle engines and suspension systems to power onboard sensors and electronics. Moreover, MEMS piezoelectric energy harvesters find applications in consumer electronics, wearable devices, IoT (Internet of Things) systems, and medical implants, providing a reliable and sustainable power source for various electronic functionalities.Despite the promising prospects of MEMS piezoelectric vibrational energy harvesting, several challenges and opportunities exist that warrant further research and development [5-9]. Optimization of design and fabrication processes is essential to enhance the efficiency and reliability of MEMS energy harvesters, particularly in harsh operating environments with high levels of vibration. Improving energy conversion efficiency and power output remains a priority to meet the increasing power demands of emerging electronic applications. Additionally, advancements in materials science and nanotechnology hold the potential to unlock new avenues for enhancing the performance and scalability of MEMS piezoelectric energy harvesters [10-12].

Piezoelectric energy harvesting from roads and vehicles has garnered increasing attention as a sustainable solution for energy generation and infrastructure improvement. The principle behind this technology lies in the ability of piezoelectric materials to convert mechanical vibrations into electrical energy. As vehicles traverse roadways, they impart mechanical stress on the surface, causing it to deform slightly. By embedding piezoelectric elements within the road infrastructure, these deformations can be harnessed to generate electricity. One of the significant advantages of piezoelectric energy harvesting is its potential for integration into existing infrastructure without significant disruption. These systems can be seamlessly integrated into roads, sidewalks, and traffic management systems, making them an attractive option for smart city initiatives and sustainable urban development. Furthermore, the scalability of piezoelectric energy harvesting allows for deployment in various settings, from busy urban intersections to remote rural roads, providing opportunities for energy generation across diverse environments [13-15].In addition to electricity generation, piezoelectric energy harvesting systems offer ancillary benefits such as traffic monitoring and infrastructure health monitoring. By incorporating sensors alongside piezoelectric elements, these systems can gather valuable data on traffic patterns, vehicle counts, and road conditions.

This data can be used to optimize traffic flow, improve safety, and inform infrastructure maintenance schedules. However, the widespread adoption of piezoelectric energy harvesting faces several challenges. Durability is a critical concern, as these systems must withstand constant exposure to heavy vehicles, weather conditions, and other environmental factors [16-18]. Additionally, optimizing the efficiency of energy conversion and storage mechanisms is essential to maximize energy yield and minimize waste. Cost-effectiveness is also a consideration, as the initial installation and maintenance costs must be balanced against the long-term benefits and energy savings. Despite these challenges, ongoing research and development efforts are driving innovation in the field of piezoelectric energy harvesting. Advances in materials science, sensor technology, and energy management systems hold the promise of overcoming current limitations and unlocking the full potential of this sustainable energy solution. With continued investment and collaboration, piezoelectric energy harvesting from roads and vehicles has the potential to play a significant role in shaping the future of transportation, energy, and urban infrastructure [19-20].

II. SIMULATION PROCESS

MEMS (Micro-Electro-Mechanical Systems) piezoelectric energy harvesting has emerged as a promising technology for converting mechanical vibrations into electrical energy. This innovative approach utilizes the direct piezoelectric effect, whereby certain materials generate electric charge in response to mechanical strain. By leveraging this phenomenon, MEMS devices can effectively capture ambient vibrations and convert them into usable electrical power. This introduction provides an overview of the principles underlying MEMS piezoelectric energy harvesting, with a focus on the mathematical equations governing its operation. The dynamical behavior of MEMS piezoelectric energy harvesters is described by a set of equations that capture both mechanical and electrical aspects of the system. These equations incorporate fundamental principles from mechanics and electromagnetism to model the device's response to external stimuli.

$$m_{eq}z''+c_{eq}z'+k_{eq}z+\theta_1 V=-m_{eq}(Ky'')+c_{air}(Ky')$$

This equation accounts for the mechanical motion of the device, considering parameters such as equivalent inertia m_{eq}, mechanical damping c_{eq}, and stiffness k_{eq}. The term $\theta_1 V$ represents the force induced by the piezoelectric material, while $c_{air}(Ky')$ captures air resistance effects.

The simulation program described adopts a simplified approach to predict the displacement of a cantilever's tip. While an elastic beam can be rigorously modeled using partial differential equations to determine its shape dynamically, the program opts for an ordinary differential equation method. This streamlined technique, known as lumped-parameter modelling, replaces the complex interaction of the tip with the rest of the structure with equivalent parameters. By employing lumped-parameter modelling, the program efficiently calculates the displacement of the cantilever's tip. However, it's important to recognize that this method primarily predicts the behaviour of the cantilever's first oscillation mode. Consequently, the simulations generated by the program are most accurate for frequencies near or below the first

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resonance of the structure. Nonetheless, it's noteworthy that these lower frequency oscillations are often where energy harvesting is most effective. The determination of the total inertia of the system employs the Lord Rayleigh approximation, a method that offers a simplified means to assess inertia. In this estimation, the focus is on incorporating the mass of the beam, acknowledging its comparatively minor impact relative to the substantial contribution of the proof mass.

$$m_{eq} = \frac{33}{140} m_{beam} + m_{proof}$$

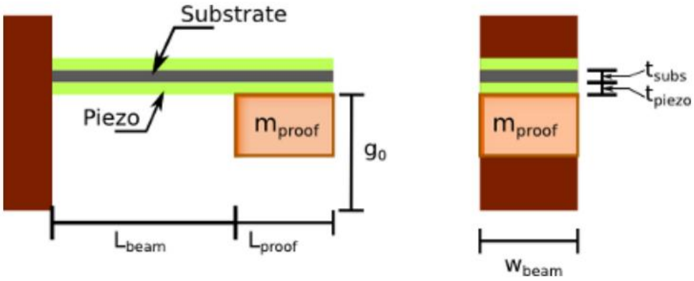

Fig. 1Schematic of the geometry of the cantilevered beam.

In the context of MEMS (Micro-Electro-Mechanical Systems) harvesting systems, which aim to convert mechanical vibrations into electrical energy, an analogy can be drawn to a linear RC (Resistor-Capacitor) circuit. This analogy provides a simplified framework to understand the behavior of the system. In this analogy, the piezoelectric element within the MEMS device is likened to a parallel-plate capacitor. This comparison arises from the fact that piezoelectric materials have the unique property of generating an electric charge in response to mechanical stress or strain. When subjected to vibrations, such as those encountered in road traffic or machinery, the piezoelectric material undergoes deformation, resulting in the accumulation of electrical charge on its electrodes. This charge accumulation effectively mimics the behavior of a capacitor in an electrical circuit, where charge is stored between two plates.Furthermore, the forward electromechanical coupling, which describes the conversion of mechanical energy into electrical energy, is represented in the analogy as a current source within the electrical circuit. This current source symbolizes the flow of electrical current generated by the piezoelectric material in response to mechanical vibrations. Essentially, it serves as the driving force for the electrical circuit, supplying the energy harvested from mechanical vibrations.

III. RESULTS AND DISCUSSIONS

Simulation results are plotted in Fig. 2 to Fig. 5 When comparing the power generated by PZT (Lead Zirconate Titanate), AlN (Aluminum Nitride), and PVDF (Polyvinylidene Fluoride) piezoelectric materials, several trends emerge. These trends suggest that while all materials experience diminishing power generation with increased thickness, PVDF may offer some variability in performance compared to PZT and AlN, highlighting the importance of material selection based on specific application requirements and desired power output efficiency. Table I presents computed results pertaining to the thickness of PZT (Lead Zirconate Titanate) piezoelectric material utilized in an energy harvesting system.The average power generated by the system gradually decreases with increasing thickness of the PZT material. For instance, with a thickness of 200 units, the average harvested power is approximately 6.3687e-06 microwatts (uW), whereas with a thickness of 250 units, it decreases to approximately 2.9571e-06 uW. Similarly, the peak power, representing the maximum power output during operation, follows a decreasing trend as the thickness of the PZT material increases. At a thickness of 200 units, the peak power is around 2.7836e-05 uW, while at 250 units, it decreases to approximately 1.2125e-05 uW. The power density, indicating the amount of power generated per unit volume of the piezoelectric material, also decreases with increasing thickness. For example, with a thickness of 200 units, the power density is approximately 1.1738e-07 milliwatts per cubic centimeter (mW/cm^3), whereas with a thickness of 250 units, it reduces to approximately 4.6024e-08 mW/cm^3.The efficiency of converting mechanical vibrations into electrical power, represented by the power-to-acceleration ratio, experiences a slight decrease with increasing thickness of the PZT material. At a thickness of 200 units, the ratio is approximately 0.00071489 uW/(g RMS)^2, while at 250 units, it decreases to approximately 0.00032918 uW/(g RMS)^2.

TABLE I COMPUTED OUTPUT WITH RESPECT TO THICKNESS OF PZT PIEZOELECTRIC.

Thickness	**Average harvested power**	**Peak power**	**Power density**	**Power-to-acceleration ratio**
200	6.3687e-06 [uW]	2.7836e-05 [uW]	1.1738e-07 [mW/cm^3]	0.00071489[uW/(g RMS)^2]
210	5.3561e-06 [uW]	2.3011e-05 [uW]	9.5213e-08 [mW/cm^3]	0.00059531[uW/(g RMS)^2]
220	4.6044e-06 [uW]	1.9738e-05 [uW]	7.9042e-08 [mW/cm^3]	0.00051471[uW/(g RMS)^2]
230	3.8472e-06 [uW]	1.7841e-05 [uW]	6.3851e-08 [mW/cm^3]	0.00043338[uW/(g RMS)^2]
240	3.5394e-06 [uW]	1.5345e-05 [uW]	5.6855e-08 [mW/cm^3]	0.00039488[uW/(g RMS)^2]
250	2.9571e-06 [uW]	1.2125e-05 [uW]	4.6024e-08 [mW/cm^3]	0.00032918[uW/(g RMS)^2]

The table outlines computed results concerning the thickness of AlN (Aluminum Nitride) piezoelectric material in an energy harvesting system. The average power output of the system displays a diminishing trend as the thickness of the AlN piezoelectric material increases. For instance, at a thickness of 200 units, the average harvested power is approximately 8.1846e-10 microwatts (uW), while at 250 units, it decreases to about 4.4934e-10 uW.Similarly, the peak power, which represents the maximum power output during operation, also decreases with increasing thickness of the AlN material. At 200 units thickness, the peak power is around 3.9623e-09 uW, while at 250 units, it reduces to approximately 2.1311e-09 uW. The power density, indicating the amount of power generated per unit volume of the piezoelectric material, exhibits a decreasing trend as well. With a thickness of 200 units, the power density is approximately 9.6267e-12 milliwatts per cubic centimetre (mW/cm^3), while at 250 units, it reduces to about 4.4602e-12 mW/cm^3.The efficiency of converting mechanical vibrations into electrical power, represented by the power-to-acceleration ratio, experiences a slight decrease with increasing thickness of the ALN material. At a thickness of 200 units, the ratio is approximately 9.1872e-08 uW/(g RMS)^2, while at 250 units, it decreases to approximately 5.0218e-08 uW/(g RMS)^2.

TABLE II COMPUTED OUTPUT WITH RESPECT TO THICKNESS OF ALN PIEZOELECTRIC.

Thickness	**Average harvested power**	**Peak power**	**Power density**	**Power-to-acceleration ratio**
200	8.1846e-10 [uW]	3.9623e-09 [uW]	9.6267e-12 [mW/cm^3]	9.1872e-08[uW/(g RMS)^2]
210	7.3066e-10 [uW]	3.8643e-09 [uW]	8.2873e-12 [mW/cm^3	8.1664e-08[uW/(g RMS)^2]
220	6.2218e-10 [uW]	2.8411e-09 [uW]	6.8139e-12 [mW/cm^3]	6.9926e-08[uW/(g RMS)^2]
230	5.8872e-10 [uW]	3.2159e-09 [uW]	6.2328e-12 [mW/cm^3]	6.6072e-08[uW/(g RMS)^2]
240	5.0089e-10 [uW]	2.0734e-09 [uW]	5.1321e-12 [mW/cm^3]	5.5942e-08[uW/(g RMS)^2]
250	4.4934e-10 [uW]	2.1311e-09 [uW]	4.4602e-12 [mW/cm^3]	5.0218e-08[uW/(g RMS)^2]

TABLE III analyzes the computed results concerning the thickness of PVDF (Polyvinylidene Fluoride) piezoelectric material in an energy harvesting system. The average power output of the system shows variation with the thickness of the PVDF material. For instance, at a thickness of 200 units, the average harvested power is approximately 2.199e-09 microwatts (uW), while at 250 units, it increases to about 2.0604e-09 uW. Similarly, the peak power, representing the maximum power output during operation, exhibits fluctuations with varying thickness. At 200 units thickness, the peak power is around 1.8819e-08 uW, while at 250 units, it is approximately 1.6858e-08 uW. The power density, denoting the amount of power generated per unit volume of the PVDF piezoelectric material, also varies. With a thickness of 200 units, the power density is approximately 2.5729e-11 milliwatts per cubic centimeter (mW/cm^3), while at 250 units, it decreases slightly to about 2.0381e-11 mW/cm^3.The efficiency of converting mechanical vibrations into electrical power, indicated by the power-to-acceleration ratio, demonstrates some fluctuations with different thicknesses of the

PVDF material. At 200 units thickness, the ratio is approximately 2.4225e-07 uW/(g RMS)^2, while at 250 units, it increases to around 2.2919e-07 uW/(g RMS)^2.

TABLE III COMPUTED OUTPUT WITH RESPECT TO THICKNESS OF PVDF PIEZOELECTRIC.

Thickness	**Average harvested power**	**Peak power**	**Power density**	**Power-to-acceleration ratio**
200	2.199e-09 [uW]	1.8819e-08 [uW]	2.5729e-11 [mW/cm^3]	2.4225e-07[uW/(g RMS)^2]
210	1.6978e-09 [uW]	1.5508e-08 [uW]	1.9166e-11 [mW/cm^3]	1.9236e-07[uW/(g RMS)^2]
220	2.0822e-09 [uW]	1.481e-08 [uW]	2.2713e-11 [mW/cm^3]	2.3518e-07[uW/(g RMS)^2]
230	5.8872e-10 [uW]	3.2159e-09 [uW]	6.2328e-12 [mW/cm^3]	6.6072e-08[uW/(g RMS)^2]
240	1.9156e-09 [uW]	1.4194e-08 [uW]	1.9567e-11 [mW/cm^3]	2.1649e-07[uW/(g RMS)^2]
250	2.0604e-09 [uW]	1.6858e-08 [uW]	2.0381e-11 [mW/cm^3]	2.2919e-07[uW/(g RMS)^2]

Figure 2 to Figure 5

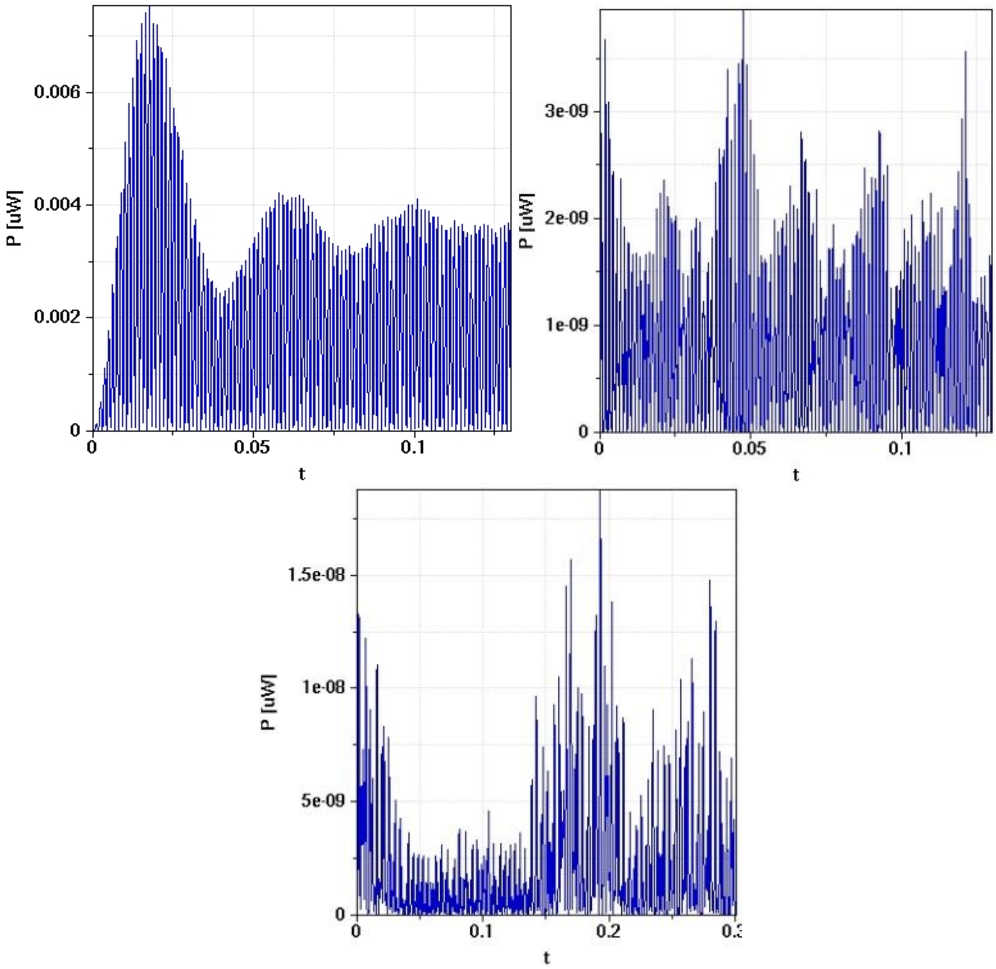

Fig. 2(a) PZT, (b) AlN, and (c) PVDF generated power with respect to simulation time.

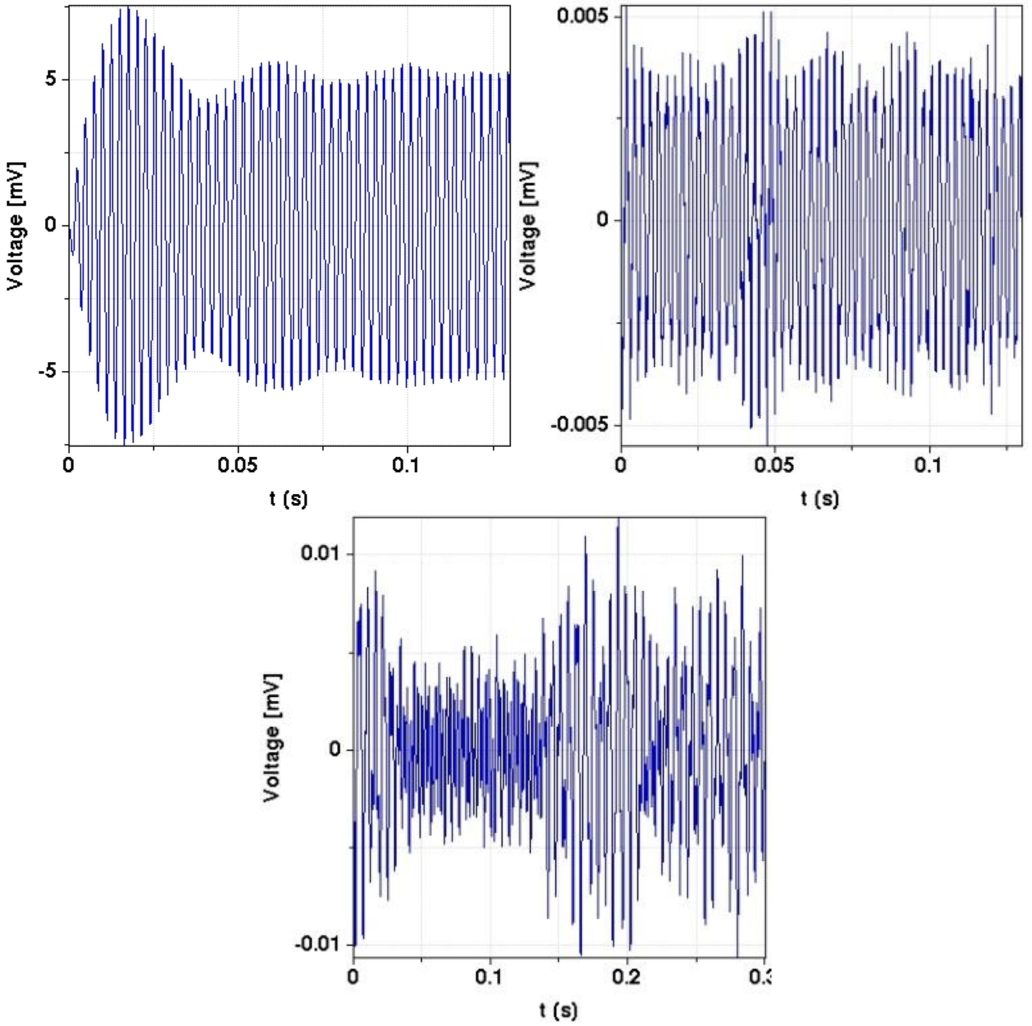

Fig. 3(a) PZT, (b) AlN, and (c) PVDF generated voltage with respect to simulation time.

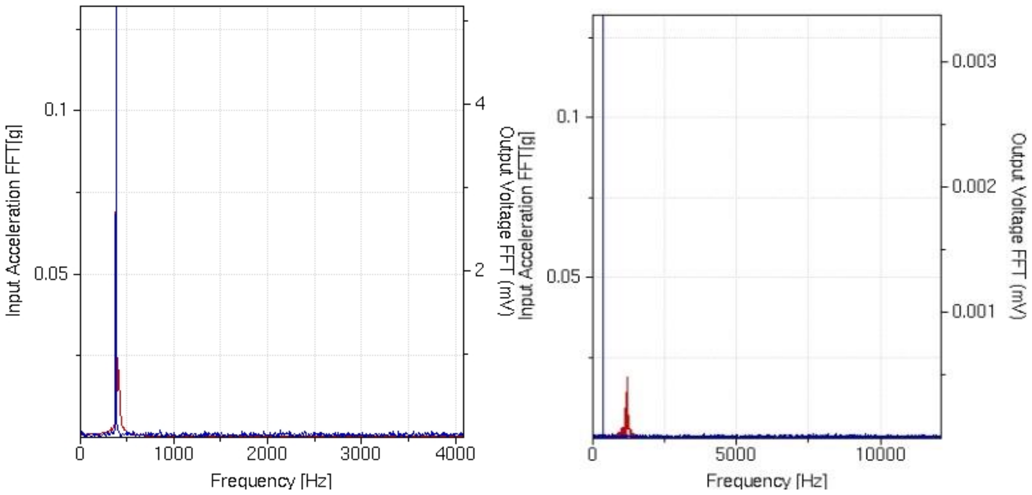

Fig. 4 (a) PZT, and (b) AlN PVDF input/output FFT with respect to frequency.

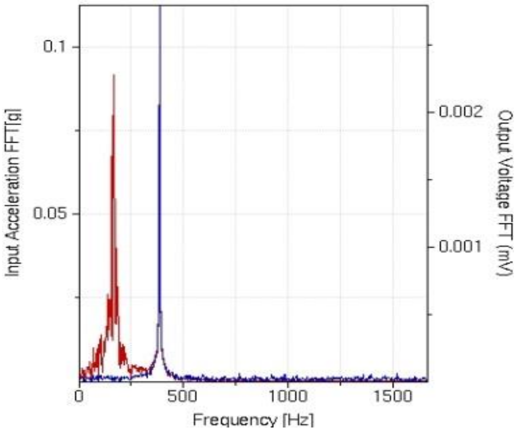

Fig. 4(c) PVDF input/output FFT with respect to frequency.

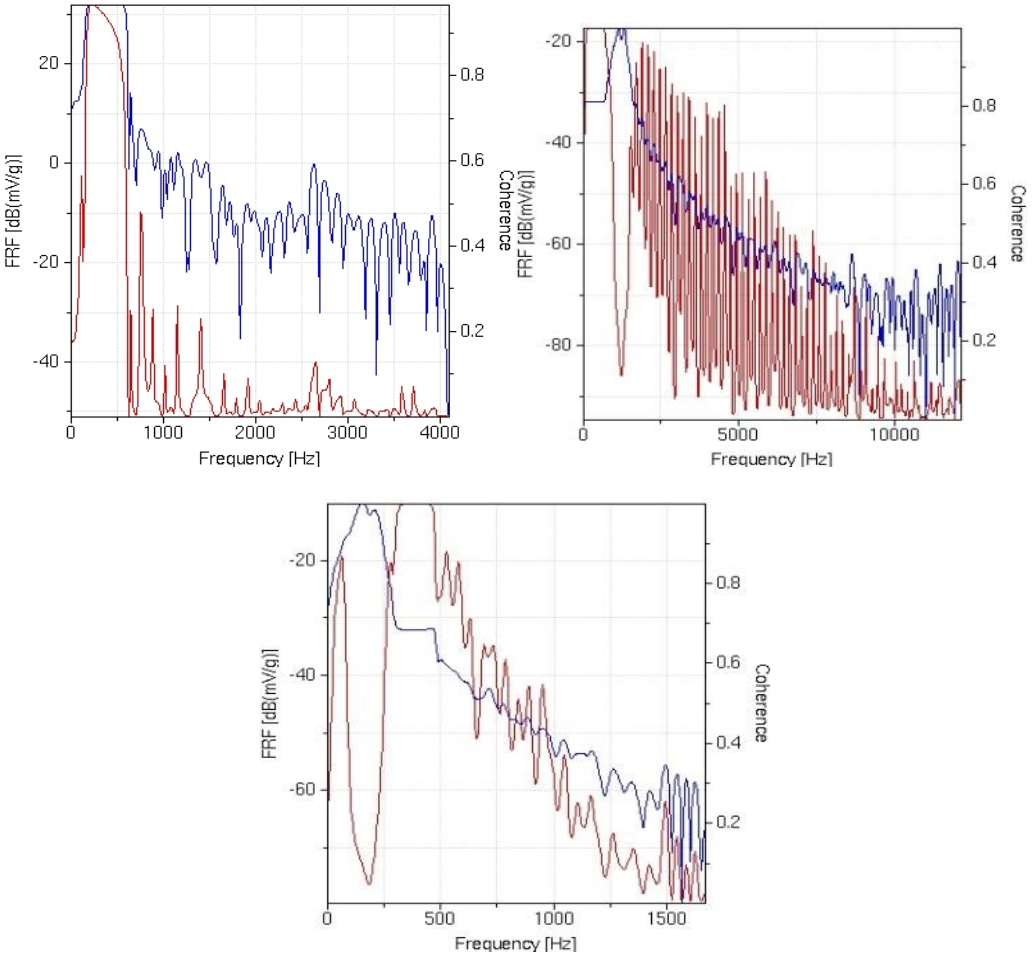

Fig. 5(a) PZT, (b) AlN, and (c) PVDF frequency response function with respect to frequency.

IV. CONCLUSION

In conclusion, the comparison of PZT, AlN, and PVDF piezoelectric materials highlights the varying performance characteristics and suitability for energy harvesting applications Comparing the results of piezoelectric materials, namely PZT, AlN, and PVDF, provides valuable insights into their performance characteristics in energy harvesting applications. Across various thicknesses, PZT consistently demonstrates superior average harvested power and peak power outputs compared to AlN and PVDF. Additionally, PZT exhibits higher power densities, indicating a more efficient conversion of mechanical vibrations into electrical power per unit volume. The power-to-acceleration ratio, a measure of efficiency, is also notably higher for PZT compared to AlN and PVDF. While AlN demonstrates moderate performance across these metrics, PVDF generally lags behind PZT and AlN in terms of power output and efficiency. However, PVDF may offer advantages in specific applications due to its unique material properties. Engineers evaluating these materials for energy harvesting systems should consider factors such as power output requirements, efficiency, and application-specific constraints to make informed decisions regarding material selection.

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