Beams-driven structures for piezoelectric energy harvesting/sensor and piezoelectric actuator

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Abstract

Beams-driven structures are structures that use beams to support their weight. The beams are typically arranged in a way that distributes the weight of the structure evenly. Beams-driven structures are often used in buildings, bridges, and other complicated structures. Beams-driven structures are robust, capable of supporting heavy loads, and popular due to their ease of construction. Their advantages include strength, versatility, and durability to withstand wear and tear. Piezoelectric materials are able to convert mechanical energy into electrical energy and vice versa. This is known as the direct and inverse piezoelectric effect. The direct piezoelectric effect is the mechanism through which piezoelectric energy harvesters operate. When a piezoelectric material is deformed, it generates an electric potential. The inverse piezoelectric effect is used in piezoelectric actuators, which convert electrical energy into mechanical energy.

Piezoelectric energy harvesters have shown great promise as a way of powering small-scale electronic devices, such as sensors and monitoring equipment, in situations where battery replacement is costly or difficult. They can also be used to collect and process energy from the environment. The unique properties of piezoelectric materials make them useful in various applications, such as sensors, actuators, and energy harvesting. The current study presents different beams-driven structures for piezoelectric energy harvesting/sensor and piezoelectric actuator. The primary simulation studies consist of eigenfrequencies and frequency domain analysis of piezoelectric energy harvesters and actuators using COMSOL multiphysics. The various beam unit-cell shapes are considered hexagonal, square, and octagonal; reported the cell shape for optimum performance among the mentioned cell shapes. Furthermore, the impact of various beam cross-sections (circular, square, and hexagonal) on the output of piezoelectric energy harvesters and actuators is studied. Finally, parametric studies are performed on the piezoelectric materials for better performance.

Keywords: Smart materials and structures, energy harvester, sensor, actuator, COMSOL multiphysics, vibration control/isolation.

1. Introduction

Beams-driven structures refer to constructions or systems where beams, which are long, sturdy pieces of material (such as wood, steel, concrete, etc), are the primary components influencing the design and functionality of the structure. These beams play a central role in supporting the load and transferring forces within the structure. The term implies that the design and functionality of the structure heavily rely on these beams, which are strategically placed and used to bear weight, provide support, and maintain the overall stability of the building or system. Beams can be arranged and utilized in various ways to create diverse types of structures, such as bridges, buildings, or frameworks, depending on the specific engineering and architectural requirements [1]. Piezoelectric materials are materials that have a special property: when you subject them to mechanical stress or pressure, they generate a small electric charge. In simpler terms, if you squeeze, bend, or deform these materials, they produce a bit of electrical voltage. What's fascinating is that the reverse is also true – if an electric voltage is applied to these materials, they can slightly change shape or deform. These materials are valuable because of their ability to convert mechanical energy into electrical energy and vice versa. They're used in various devices such as microphones, sensors, and actuators due to their capacity to respond to physical changes and convert them into electrical signals, making them vital in many types of technology, biological, and engineering applications [2].

Beams-driven structures for piezoelectric energy harvesters/sensors are designs where the use of beams plays a crucial role in creating devices that can generate electrical energy or detect physical changes in the environment. These structures are engineered to use beams to manipulate piezoelectric materials, allowing them to convert mechanical stress or movement into electrical energy, or to sense and measure changes in the environment. This combination of beams and piezoelectric materials enables the creation of systems that can harvest energy from movement or vibrations or be used as sensors to detect and respond to various forces or conditions [3]. Beam-driven structures for piezoelectric actuators are designs that use beams to create devices capable of producing movement or mechanical action through the use of piezoelectric materials. These structures rely on beams to manipulate piezoelectric elements, which, when activated by an electric charge, cause the actuator to move, push, or perform mechanical tasks. This setup allows for the creation of actuators that can convert electrical energy into physical movement, making them useful in various applications like robotics, precision equipment, vibration control/isolation, and other mechanical systems.

The distinctive characteristic of piezoelectric structures enables their application in diverse fields, such as health monitoring for infrastructure like bridges and human health. Moreover, their functionality extends to vibration control and isolation in various systems and machinery. This unique attribute permits these structures to serve multiple purposes, including detecting structural integrity in bridges and other infrastructure, monitoring vital signs and health indicators in human bodies, and aiding in controlling and reducing vibrations in equipment or systems. This versatility underscores their significance in maintaining safety, enabling health tracking, and improving the stability of various mechanical setups [4]. In this study, we explored the different unit cell shapes of beams, including square, hexagonal, and octagonal, used in structures where common input conditions for all beam shapes. These beams have different cross-sections like circular, square, and hexagonal. Focused on the most commonly used piezoelectric materials for a comprehensive analysis of materials and exploring a range of these materials to understand their behavior and potential applications in this context. The simulation involves a systematic and detailed process demonstrated in a step-by-step flow diagram shown in Figure 1. This visual representation illustrates the specific stages of our model simulation, allowing us to understand and replicate the process.

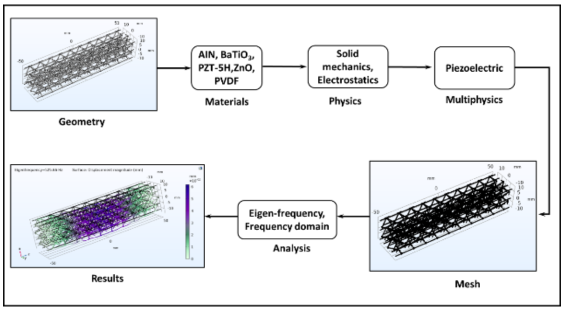

Figure 1. The flow chart of the step-by-step simulation procedure for COMSOL Multiphysics

2. Methodology

The constitutive equations of the piezoelectric model outline the connection between the electrical and mechanical characteristics of piezoelectric materials. They encompass a range of physical traits and behaviors displayed by these materials, aiding in comprehending how they transform mechanical energy into electrical energy and vice versa. The constitutive equations governing piezoelectric sensors are rooted in the materials' distinctive properties, especially piezoelectric coefficients. These equations are pivotal as they delineate the intricate link between the mechanical stresses or strains applied to the material and the resulting electrical response. Understanding these equations is crucial for unraveling the operational mechanisms of piezoelectric sensors. Furthermore, they play a fundamental role in designing systems where mechanical stimuli can be effectively translated into electrical signals, enabling precise sensing or measurement functionalities.

Direct piezoelectric effect: This equation relates the electric displacement (D) to the mechanical stress (σ) and electric field (E):

$$D = d * \sigma + \varepsilon * E \qquad (1)$$

Converse piezoelectric effect: This equation relates the mechanical strain (S) to the electric field (E) and mechanical stress (σ):

$$S = s * E + c * \sigma \qquad (2)$$

Where d is the piezoelectric stress constant, ε is the dielectric permittivity, s is the piezoelectric strain constant, and c is the elastic compliance.

The constitutive equations for piezoelectric actuators delineate the connection between the electrical and mechanical behaviors exhibited by piezoelectric materials within the actuator framework. These equations encapsulate the relationship of an applied electric field inducing mechanical deformation or displacement. The constitutive equations are usually written using math symbols and include special numbers or letters specific to the piezoelectric material being studied. They're essential in creating and studying systems that convert movements into electrical energy. They help engineers predict and improve how well these devices work.

Initially, the beams-driven structures cad models are imported in the geometry window to build up the geometry. The imported CAD geometry is the basis for further analysis and simulations within the COMSOL platform, allowing users to proceed with additional steps and, after successfully importing geometry, specifying the material properties from a material library of COMSOL. Selecting material properties means defining the specific traits and attributes of the materials utilized in simulations. This includes detailing parameters like density, Young's modulus, Poisson's ratio, and other pertinent material characteristics essential for accurately representing the behavior of the materials within the simulated setup. These properties are fundamental in enabling precise analysis and predictions of how the material will respond to various physical phenomena within the simulation.

In a piezoelectric COMSOL model, defining physics boundary conditions involves setting parameters that govern how the material interacts with its surroundings. This includes specifying factors such as electrical contacts, mechanical constraints, and the application of electric potentials or mechanical loads on the boundaries of the model. These conditions define how the piezoelectric material responds to applied electric fields, mechanical stresses, or any other environmental factors. The boundary conditions are essential in accurately representing the behavior of the piezoelectric material and its interaction with the surrounding environment within the simulation. The meshing process determines the accuracy of the simulation by influencing the precision of calculations and analysis, as well as the computational resources required for the simulation. A finer mesh provides more accurate results but requires more computational power, while a coarser mesh reduces computational demands but might sacrifice precision. The goal is to find a balance that ensures accurate simulation results without overly taxing computational resources. In the present study, the tetrahedral mesh element is used and suitable for 3D beams-driven structures. The mesh parameters are maximum element size is 5.5 mm, minimum element size is 0.4 mm, maximum element growth rate is 1.4, curvature factor is 0.4, and resolution of narrow regions is 0.7.

The analysis involves solving the mathematical equations and physical principles based on the input parameters, boundary conditions, and the defined mesh. Initially, the eigenfrequency study was conducted to determine the natural frequencies of the system for specified end conditions. Eigenfrequency analysis in COMSOL refers to a computational procedure used to determine the natural frequencies of a given system or structure. This process involves solving an eigenvalue problem within the software to calculate the frequencies at which the system vibrates without external influences. It helps identify the essential resonant frequencies and corresponding mode shapes, offering insights into the system's dynamic behavior. Further, the frequency domain study explored in COMSOL involves analyzing the behavior of a system within the frequency range. The frequency domain analysis was conducted for various parametric system changes mentioned in Figure 2.

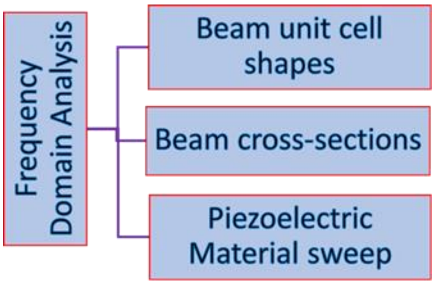

Figure 2. The frequency domain analysis of the system for different parameters.

Different unit-cell shapes of structures, including hexagonal, square, and octagonal, are analyzed, aiming to determine the most effective cell shape for optimal performance among those considered. Additionally, the investigation delves into the influence of various beam cross-sections (circular, square, and hexagonal) on the output of piezoelectric energy harvesters and actuators. Finally, parametric studies are carried out on piezoelectric materials to enhance overall performance. The beam unit cell has a 10*10*10 mm size. The beam's ball diameter is 1.5 mm, and the beam cross-section size is 0.5 mm. The dimensions considered for the beams-driven structure are 20*20*100 mm. The unit cell and beam cross-sections are shown in Figure 3.

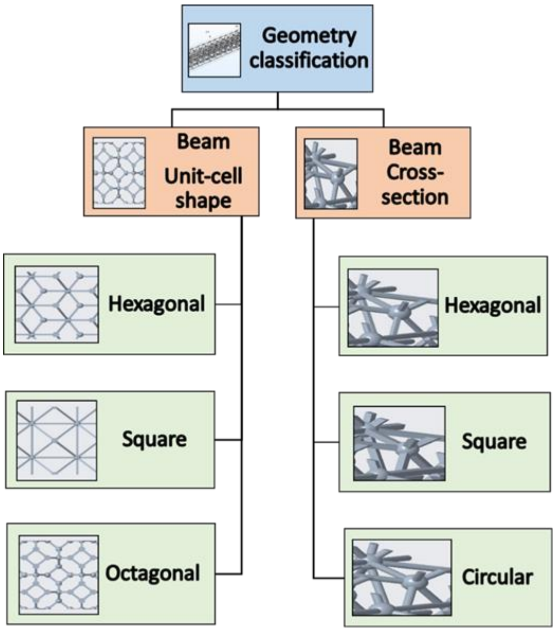

Figure 3. The various beam shapes and beam cross-sections of the structures.

3. Free vibration analysis

In this analysis, the fixed-fixed boundary condition considered for beams-driven structures is allowed to vibrate freely from its initial position without any imposed displacements or loads. The investigation primarily focuses on understanding the natural frequencies, mode shapes, and beam behavior under these natural vibrational conditions. By studying the free vibration characteristics, one can determine the natural modes of oscillation and their associated frequencies, aiding in evaluating the beam's structural properties and dynamic behavior without external disturbances. Table 1 shows the first six natural frequencies of the beam-driven structures in Hz units. The natural frequencies and mode shapes of the beam-driven structures with circular cross-sections are shown in Figure 4.

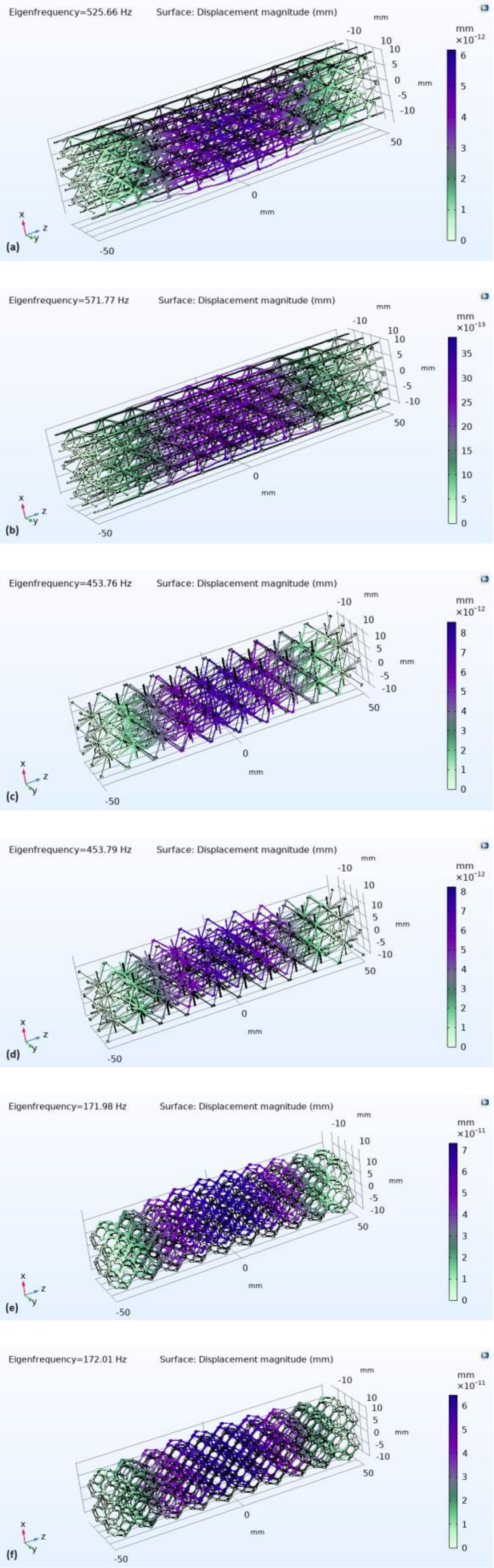

Figure 4. The first two natural frequencies and respective mode shapes of (a,b) hexagonal,(c,d) square, and (e,f) octagonal beam unit cell shape structures.

Table 1. The first six natural frequencies of the beams-driven structures.

Beams-driven structure unit cell	Natural frequencies (Hz)
Hexagonal	525.66, 571.77, 960.79, 1087.5, 1153.2, 1176.7
Square	453.76, 453.79, 964.6, 1003.5, 1003.8, 1062.7
Octagonal	171.98, 172.01, 267.94, 392.35, 392.51, 538.24

4. Piezoelectric energy harvester

The model integrates solid mechanics and electrostatics physics to attain comprehensive piezoelectric multiphysics outcomes. The fixed-end constraint is given to both ends of the structure. The ground and floating potential are given opposite surfaces to each other. The boundary load was given as total force to the boundary surface (100 N), and this boundary was maintained the same for all simulations of the PEH. The settings and configuration for these conditions are visually presented in Figure 5.

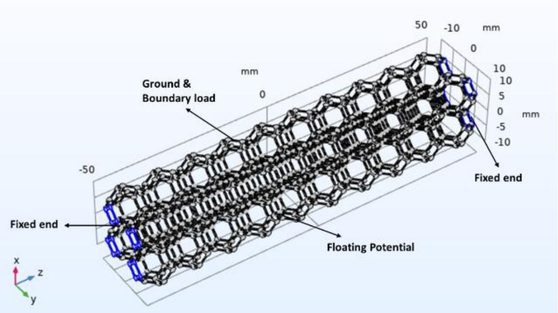

Figure 5. The boundary conditions of the Beams-driven structure for PEH.

The study aims to examine the piezoelectric energy harvester's voltage response across two distinct parameters: (i) various beam unit cells: This involves investigating how the voltage response of the PEH varies as the configuration of beam unit cells (octagonal, hexagonal, and square) changes. It aims to understand how alterations in the structural design, precisely the shape of unit cells in the beam, impact the generated voltage within the piezoelectric energy harvester. (ii) various beam cross-sections: This part of the analysis focuses on observing and comparing the PEH voltage response with different beam cross-sectional shapes. It seeks to explore how the geometry of the beam, such as circular, square, or hexagonal cross-sections, affects the voltage output of the piezoelectric energy harvester. Figure 6a shows the different beam unit cells with circular beam cross-section of the PEH. Figure 6b shows the octagonal beam unit cell PEH configuration with various beam cross-sections.

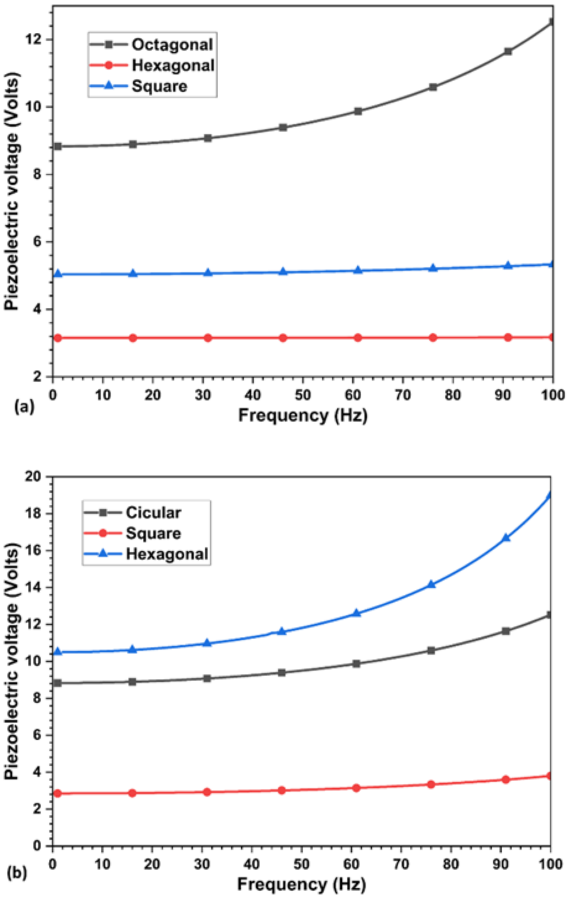

Figure 6. Voltage response of PEH (a) at various beam unit cells with circular beam cross-section, (b) at various beam cross-sections of the octagonal beam unit cell.

From Figure 6, in addition, the material parametric sweep is analyzed for an octagonal beam unit cell with a hexagonal beam cross-section. Figure 7 shows the materials considered for the parametric sweep study.

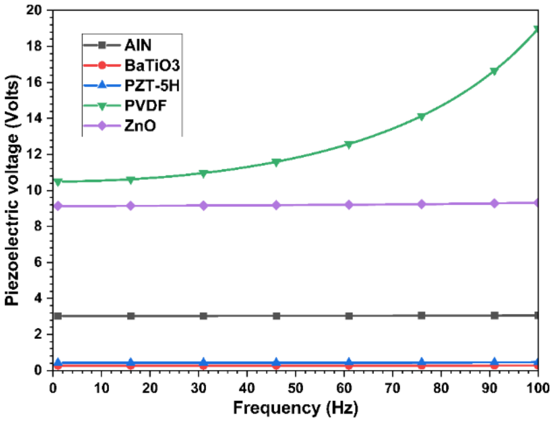

Figure 7. The voltage response of an octagonal beam unit cell with a hexagonal beam cross-section PEH at various piezoelectric materials.

5. Piezoelectric actuator

The comprehensive piezoelectric multiphysics actuator model combines principles from solid mechanics and electrostatics to yield thorough outcomes. Both ends of the structure are constrained, maintaining fixed positions. Opposite surfaces are assigned as ground and electrical potential, ensuring an electrical charge is applied through the electrical potential node across the required structure surface. An electrical potential of 100 volts is consistently applied to the boundary surface throughout all simulations. Figure 8 visually illustrates the boundary conditions and configuration used to establish these specific conditions in the model.

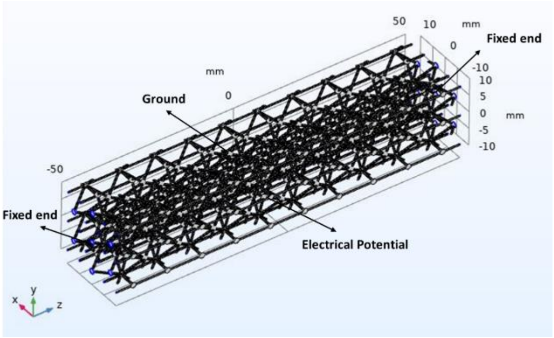

Figure 8. The boundary conditions of the Beams-driven structure for PEA.

The present investigation explored the piezoelectric actuator’s dynamic response by exploring two specific parameters:(i) various beam unit cells: This part of the study delves into examining the piezoelectric actuator (PEA) dynamic behavior concerning changes in the configuration of beam unit cells, explicitly focusing on octagonal, hexagonal, and square shapes. The aim is to understand how modifications in the structural layout, particularly altering the shape of unit cells within the beam, influence the dynamic performance of the piezoelectric actuator. (ii) various beam cross-sections: Another facet of the analysis concentrates on observing and contrasting the PEA’s dynamic response when subjected to different beam cross-sectional shapes. The objective is to investigate how the beam's geometry cross sections, like circular, square, or hexagonal, affect the dynamic output of the piezoelectric actuator. Figure 9a depicts the visual representation of the different beam unit cells with circular beam cross-sections. Figure 9b represents a hexagonal beam unit cell configuration with various beam cross-sections.

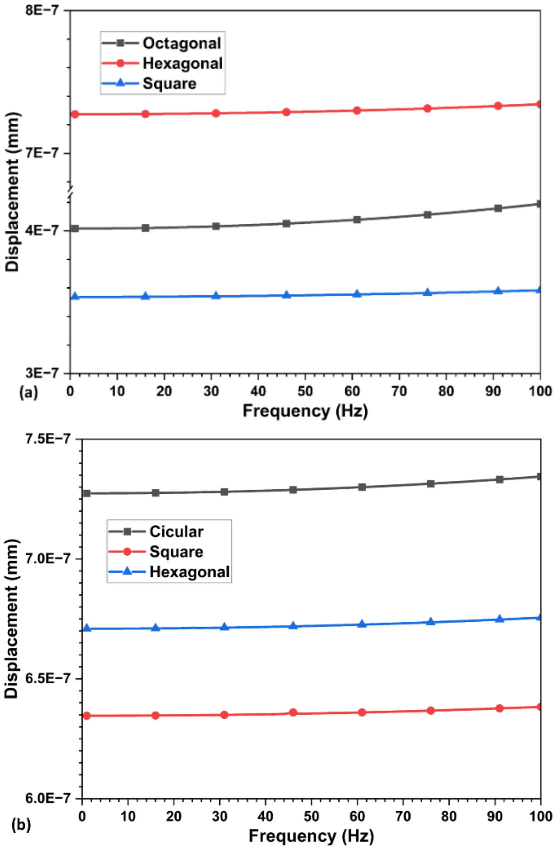

Figure 9. Dynamic response of PEA (a) at various beam unit cells with circular beam cross-section, (b) at various beam cross-sections of the hexagonal beam unit cell.

Furthermore, utilizing the information in Figure 9, the study examines a material parametric sweep concerning a hexagonal beam unit cell combined with a circular beam cross-section. The materials considered for this specific parametric sweep analysis are illustrated in Figure 10. This investigation aims to explore how variations in material properties affect the behavior and performance of the structure with this particular geometric configuration. Figure 10 visually presents the materials included and analyzed within this parametric sweep study.

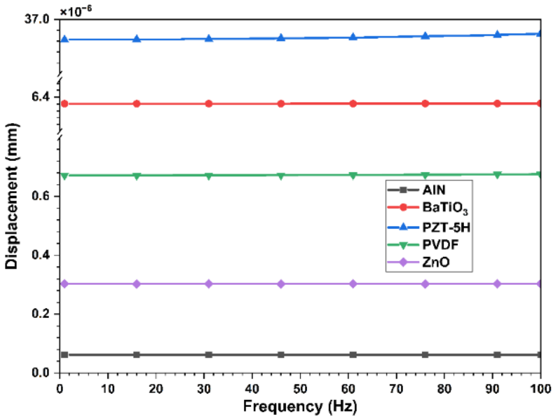

Figure 10. The dynamic response of a hexagonal beam unit cell with a circular beam cross-section PEA at various piezoelectric materials

5. Conclusion

The primary simulation analysis involves investigating eigenfrequencies and conducting frequency domain analysis for piezoelectric energy harvesters and actuators using the COMSOL Multiphysics. Various beam unit-cell shapes, including hexagonal, square, and octagonal, are assessed to determine the cell shape that yields the best performance among these options. Additionally, the study explores how different beam cross-sections, such as circular, square, and hexagonal shapes, affect the output of piezoelectric energy harvesters and actuators. Furthermore, parametric studies are conducted on piezoelectric materials to enhance overall performance and optimize the system. The observed outcomes from the simulation studies are:

i. Piezoelectric energy harvester
   a. Beam unit cells shape: octagonal > square > hexagonal.
   b. Beam cross-sections: hexagonal > circular > square.
   c. Piezoelectric materials: PVDF > ZnO > AIN > PZT-5H > $BaTiO_3$.
ii. Piezoelectric actuator
   a. Beam unit cells shape: hexagonal > octagonal > square.
   b. Beam cross-sections: circular > hexagonal > square.
   c. Piezoelectric materials: PZT-5H > $BaTiO_3$ > PVDF > ZnO > AIN.

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