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Investigation and Numerical Simulation of Different Piezoelectric Bimorph Cantilever Designs for Energy Harvesting

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Abstract— The study investigates the dynamic performance and energy harvesting efficiency of different cantilever configurations using numerical simulations. It examines factors such as material properties, geometrical parameters, and excitation conditions to optimize the design for enhanced energy harvesting capabilities. The research contributes to understanding how different cantilever designs affect the overall performance and efficiency of piezoelectric energy harvesters. Vibrational energy harvesters, also known as MEMS, have become popular due to their efficiency and ease of inclusion in microsystems. COMSOL Multiphysics was used to simulate six different forms of piezoelectric bimorph cantilevers for energy harvesting. Designs were analyzed, with each design having a distinct arrangement of proof masses. Design 01 had a rectangular cantilever with a proof mass connected to its top surface, Design 02 used a rectangular cantilever, Design 03 used a novel approach, Design 04 used a trapezoidal cantilever, and Design 05 preserved the trapezoidal form but moved the proof mass to the structure's base. Design 06 successfully completed the trapezoidal cantilever. The study found that design 04 had a significant advantage in power production efficiency at higher resistor values, surpassing design 01 in power output. The use of these varied designs allows for an exhaustive examination of piezoelectric bimorph cantilever configurations, potentially leading to insights that may enhance energy harvesting effectiveness in various applications.

Keywords: Bimorph design, COMSOL simulation, MEMS vibrational energy harvesters, Piezoelectric vibration energy harvesters.

INTRODUCTION

The proliferation of low-power devices and wireless sensor networks has heightened the demand for sustainable and cost-effective power sources [1]. One practical method of obtaining mechanical energy from human movement, machinery, and environmental vibrations is vibrational energy harvesters, also known as MEMS (Micro-Electro-Mechanical Systems) systems. These gadgets can generate electricity through mechanical vibrations, power low-power electronics, and wireless sensor networks—without external power sources [2]. One fast-expanding area of technology is micro-electro-mechanical systems or MEMS. This system integrates mechanical and electrical components on a microscale. Microelectromechanical

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system (MEMS) vibrational energy harvesters collect sound waves from the environment and transform them into electricity. Their portability, lightweight Ness, and capacity to capture energy from various sources, such as mechanical vibrations and human motions, make them superior to other energy harvesting techniques. Vibration energy harvesters made of piezoelectric materials have proven popular due to their ease of integration into microsystems and high energy conversion efficiency. The phrase "piezoelectric effect" refers to a material's capacity to develop an electrical charge in response to mechanical stress. Most of the time, resonant structures that use piezoelectric materials are designed to vibrate at a specific frequency in reaction to vibrations from the outside world [3]. When the deep structure vibrates, the piezoelectric material generates an electrical charge that can be used to power electronic devices. The design and modelling of piezoelectric vibration energy harvesters are vital to their functioning. Piezoelectric vibration energy harvesters are generally built in multiple stages: selecting the piezoelectric material, creating the resonant structure, and fine-tuning the electrical circuitry. COMSOL Multiphysics is a sophisticated finite element analysis database that allows designers to analyze the operation of piezoelectric vibration energy harvesters under various situations [4]. This research outlines a simulation and comparison of MEMS piezoelectric harvesters with 6 designs varying in dimensions made from PZT material. The piezoelectric energy harvester is made of a cantilever structure with a bimorph design, with a silicon center. We compare the produced power and voltage of the cantilever design and describe its inherent frequencies and material attributes. Moreover, using MEMS vibrational energy harvesters has numerous applications, such as in the healthcare business, where they may be utilized to power medical implants or wearable devices. The employment of these harvesters in the automobile sector may lead to the creation of self-powered sensors for monitoring different vehicle characteristics. They may also be utilized in environmental monitoring and industrial equipment, where they can power low-power wireless sensors for monitoring temperature, pressure, and other factors.

Miniature energy harvesting technologies, particularly microelectromechanical systems (MEMS), are promising solutions to operate low-power electronics in various applications. A critical component of these devices is piezoelectric materials, which can transform mechanical energy into electrical energy. The efficient conversion of vibrational electrical energy has made cantilever-based bimorph structures popular among various designs. Better energy removal is achieved by bringing the harvester's natural frequency closer to the vibration of the environment through design adjustments [5]- [6]. Lower natural frequency cantilever bimorphs better use larger piezoelectric material areas [7]. It is possible to optimize performance by incorporating sample mass and other features into the cantilever geometry, which has a flexible design and can be easily integrated into various microfabrication techniques [8]. To design and optimize piezoelectric energy harvesters, it is essential to understand the relationship between piezoelectric thickness, voltage, and energy output. According to this first principle, the voltage that a piezoelectric material can generate is proportional to the voltage applied to its thickness. Theoretically, thicker materials can cause more significant stresses [9]. A decrease in energy efficiency may occur if the material becomes less responsive to vibration due to an increase in thickness. Reduces energy conversion efficiency even further by moving the resonant frequency out of phase with the typical ambient vibrational frequency. Making thicker materials using microfabrication techniques can be a more challenging and costly. The thickness, applied voltage, and material properties of a piezoelectric material are three variables that determine the amount of energy that can be harvested from it. Although stresses can be increased using thicker materials, the total energy yield (in joules) is dependent on strain and stress [10]. The ideal thickness is achieved when the energy production is maximized through the trade-off of stress and strain. The particular needs of the application and the surrounding environment dictate this ideal value [11]. The piezoelectric coefficients impact the voltage/energy ratio and thickness, which vary across various piezoelectric materials. Other than thickness, different material properties must be considered for the harvester's optimal design. You can tune the harvester's resonant frequency to match the dominant vibrational frequencies of its environment and improve energy capture by adjusting the thickness. The longer beam magnifies the stress or force exerted on the piezoelectric material, similar to a more extended arm. As a result, a higher voltage output should be achieved in theory [18]. Maximizing energy production in piezoelectric harvesters requires finding the optimal length of the beam, although longer beams can generate higher voltages. Several factors must be considered, including the desired vibration frequency, material characteristics, and design limitations, to achieve an optimal balance between voltage gain and effective voltage capture. Possibilities for enhanced performance will arise from additional investigation into multimodal structures and form optimization [12].

LITERATURE REVIEW

In recent years, the issue of cleaner energy and more efficient power generation methods came to the forefront in response to the challenges confronted by global warming and pollution. There are a number of promising areas such as employing vibrational energy harvesters, also known as microelectromechanical systems (MEMS), which are receiving much attention. These gadgets can enable the independent powering of the low-power appliances and the wireless sensor networks. Piezoelectric-based vibrational energy harvesters have been of great interest in the energy harvesting process because of their high conversion efficiency and compatibility with the microsystem [13]. Conventionally, batteries have been the source of energy of various devices, but they have their own drawbacks like finite lifespan and high replacement rates. Energy harvesting devices are another way of solving this problem through the conversion of mechanical energy from the environment into electrical energy. Piezoelectric materials are remarkable in terms of their high conversion efficiency from mechanical vibrations to electrical energy [14]. Piezoelectric bimorph cantilevers, comprise of the bonding of two piezoelectric layers to make a beam-like structure, have become notable for vibrational energy harvesting. The piezoelectric effect is used to generate voltage by the cantilevers under mechanical vibrations. Such arrangement of proof masses, additional masses added to the cantilever, significantly affect performance. Numerical simulations, with the aid of such software as COMSOL Multiphysics, are essential for understanding the Performance of these cantilevers. Researchers have performed such simulations in order to look at the impact of design changes on natural frequencies and mode shapes. More specifically, the researchers have investigated the options of reducing the volume of the piezoelectric material and changing the proof mass configuration [14]. The simulations give the following key findings: rectangular cantilevers with proof masses placed on the surface top; trapezoidal cantilevers with proof masses at different positions, and new innovative approaches with proof masses attached in the middle of the structure. Such complex designs lay the groundwork for a detailed analysis of piezoelectric bimorph cantilever configurations and contributes to possible alterations that can improve the energy harvesting efficiency in different applications. On-going research explores new geometries, materials, and optimization techniques in order to further enhance the performance [15]. In this case, critical thinking would include identification of the assumptions supporting the design decisions, evaluation of the limitations of the utilized simulation methods, and consideration of alternatives or the factors that could impact the performance of the energy harvesters in the real world.

A. Overview of MEMS Vibrational Energy Harvesters and Their Applications

In addition to being referred to as MEMS, vibrational energy harvesters are compact devices capable of converting mechanical vibrations into electrical currents. These devices can collect mechanical energy from various sources, such as motion, vibrations of machinery, and the environment around them. Using low-power electronics, wireless sensor networks, and vibrational energy harvesters based on microelectromechanical systems (MEMS) is ideal for applications where charging or replacing batteries is either impractical or impossible. When subjected to mechanical stress, piezoelectric materials, which are the fundamental components of MEMS vibration energy harvesters, produce an electric charge. It is common practice for a resonant structure to use piezoelectric materials to respond to vibrations from the outside world by vibrating at a particular frequency [2]. Powering various electronic devices can be accomplished by utilizing the electrical charge produced by the vibrations of the piezoelectric material within the resonant structure. Among the many applications for MEMS vibrational energy harvesters are numerous applications in healthcare, structural health, and environmental monitoring [10]. MEMS vibrational energy harvesters can provide power to implanted medical devices such as insulin pumps and pacemakers. This means that these devices no longer require surgical battery replacement. It is also possible to use wireless sensor networks powered by MEMS vibrational energy harvesters to monitor the structural health of buildings, bridges, and other types of infrastructure. In addition to their applications in consumer electronics, microelectromechanical system vibrational energy harvesters are also utilized in the healthcare and infrastructure industries. For example, MEMS vibrational energy harvesters can power small electronic devices such as fitness trackers and smartwatches. This means these devices will not require batteries to be replaced as frequently as they currently do. There is a great deal of potential for MEMS vibrational energy harvesters to be utilized in providing power to low-power electronic devices. Vibrational energy harvesters, also known as microelectromechanical systems (MEMS), are an environmentally friendly and cost-effective method of powering electronic devices, and their application will only increase as technology advances.

1. Designing Piezoelectric Vibration Energy Harvesters using COMSOL Multiphysics

Power harvesters that use piezoelectric vibrations incorporate intricate mechanical, electrical, and material interactions into their design. The powerful finite element analysis tool COMSOL Multiphysics allows designers to model piezoelectric vibration energy harvesters in various situations [6]. A piezoelectric vibration energy harvester's design process usually entails multiple steps. This process includes electrical circuit optimization, resonant structure design, and piezoelectric material selection. Designers can enhance their designs' functionality with the help of COMSOL Multiphysics, a powerful tool that allows them to simulate all of these processes. The flexibility of COMSOL Multiphysics in simulating complicated geometries is a significant benefit when building piezoelectric vibration energy harvesters [16]. Using COMSOL Multiphysics to model multiple piezoelectric vibration energy harvesters of different sizes and shapes can help designers understand the impact of geometry on device performance. COMSOL Multiphysics also has the added benefit of simulating the device's electrical circuits. Through electrical circuit modelling, designers can maximize the device's power output. Achieving this requires meticulous matching of the piezoelectric material's impedance with the load's impedance. Ultimately, piezoelectric vibration energy harvesters built with COMSOL Multiphysics can be far more efficient and faster than those made without it. Suppose designers want to maximize the efficiency of their piezoelectric vibration energy harvesters. In that case, COMSOL Multiphysics is a must-have tool because it can model complex geometries and simulate electrical circuits [17]. The cantilever-based MEMS piezoelectric harvesters were built and modelled in this study using COMSOL. Lead zirconate titanate (PZT), the material utilized for the bimorph harvester's piezoelectric layers, is famous for having a high piezoelectric coefficient. In the harvester, you can find an inner layer of silicon. The simulation was run with the same boundary constraints for the cantilever, circular, and square harvesters, as shown in Figure 1. An electric circuit with a loaded resistance of 10kΩ was one of several subjects examined. Others included electrostatics and solid mechanics. The voltage and output power of the cantilever to be used are decided upon. The findings from this study may prove invaluable when it comes to optimizing and developing energy MEMS piezoelectric harvesters using PZT materials. Moreover, the model included a cantilever harvester connected to it from above. This constraint boundary condition applied to the harvesters affected their intrinsic stiffness and frequencies [13]. The performance of piezoelectric vibration energy harvesters in real-world situations can only be understood via simulation. If designers want to know how their piezoelectric vibration energy harvesters will act in different scenarios, they may use COMSOL Multiphysics, a vital tool for simulation. It is possible to model the Performance of piezoelectric vibration energy harvesters in COMSOL Multiphysics under several scenarios, such as when the external vibration source varies in both frequency and amplitude. Designers can optimize their devices' performance for specific applications by modelling their performance under various scenarios [15]-[32]. By simulating the interplay of the device's mechanical, electrical, and material characteristics, COMSOL Multiphysics is a powerful tool for studying piezoelectric vibration energy harvesters. Mechanical damping is a significant source of wasted energy. However, designers may improve device performance by precisely simulating the piezoelectric material's performance. Acting piezoelectric vibration energy harvesters in COMSOL Multiphysics has many benefits; one is that it may reveal how geometric differences affect the device's performance. To optimize the device's performance for specific uses, designers might experiment with various shapes by modelling its performance. When trying to understand how piezoelectric vibration energy harvesters work in practice, it is essential to do simulations in COMSOL Multiphysics. If designers want to make sure their piezoelectric vibration energy harvesters work as well as possible, they should use COMSOL Multiphysics. It can simulate the device's mechanical, electrical, and material properties and tell you how different shapes affect its performance [8].

B. Materials and Method

The study examined six distinct piezoelectric energy harvester designs to assess the efficiency of energy conversion. The bimorph configuration was chosen by placing two ground electrodes and two output electrodes on the outside surfaces of the cantilever. A proof mass was also fastened to the cantilever's tip to enhance the vibrational amplitude and bring the resonant frequency into phase with external stimulation. The piezoelectric material was chosen because of PZT 5A's mechanical stability, high Curie temperature, and superior piezoelectric coefficient. To model the MEMS cantilever bimorph piezoelectric harvesters, the software COMSOL Multiphysics was employed for finite element analysis. The harvesters' solid mechanics, including the piezoelectric and elastic characteristics of the PZT material, were characterized using the COMSOL mechanical module. We accounted for the capacitance and charge distribution under applied loads in our electrostatic simulations of the harvester using COMSOL's electric module. COMSOL analysis was employed to find the harvester's inherent frequencies and mode shapes. The first resonant mode was identified at 41 kHz. The electric circuit was modelled using COMSOL's circuit module, which allowed for circuit resistance and current flow simulation [19].To gain insight into the harvester's performance metrics and energy conversion efficiency, the appropriate equations within COMSOL were solved to derive the voltage output of the device.

C. Design and Discussion

The displacement amplitude reaches its highest at the beam's free end and progressively diminishes as it approaches the fixed end. The bending mode of a cantilever beam is consistent with this mode form. The harvester is linked to a circuit to harness the electrical charges that are produced efficiently. The circuit includes explicitly a resistive load. Accumulated potential energy may be transformed into useful electrical power by using the load as a sink for the electrical current that is created. The following is how the terminal connections are set up. A terminal connects the top piezoelectric membrane's bottom surface to the circuit. As seen in Figure 1 (a) and (b). This makes it easier for the electrical charges to be transferred from the generator to the circuit where the energy extraction happens. The top surface of the bottom piezoelectric membrane is similarly linked to a different circuit terminal

[14]. Due to this connection, the electrical charges produced by the bottom piezoelectric layer are directed into the circuit for energy conversion. The top surface of the top piezoelectric membrane and the bottom surface of the bottom piezoelectric membrane are grounded to maintain a constant electrical potential and guarantee the energy harvesting process operates as intended. Any charge imbalances interfering with the energy conversion are lessened by dropping these surfaces.

The piezoelectric effect is responsible for the produced voltage's evident linear rise with changing acceleration. The mechanical distortion and strain the piezoelectric material experiences increase with applied acceleration, leading to a more significant magnitude of produced electric charges. This linear connection highlights the energy harvesters' constant reaction to different degrees of mechanical input. The variations in the energy harvesters' designs can be responsible for their frequency response, voltage output, and power output variations. Because the cantilever design is less rigid, its resonance frequency is lower. This lower frequency allows for a higher displacement and strain, resulting in a higher voltage and power output. Application-wise, low-power applications needing a steady power output would be more suited for the cantilever design. The energy harvesters were modelled and analyzed for the simulation using COMSOL Multiphysics. Because PZT 5A has high piezoelectric coefficients and works well with silicon substrates, it was chosen as the piezoelectric material. Solid mechanics, electrostatics, and an electric circuit with a loaded 10-kOhm resistor were all incorporated into the simulation [13]-[24].

The cantilever design was subjected to the same boundary conditions, which comprised free boundary conditions on the outside borders of the piezoelectric layers and fixed boundary conditions on the silicon middle. In addition to comparing the output power and voltage of the bimorph cantilever piezoelectric harvesters, we also studied performance under a range of acceleration levels. These results demonstrate the importance of considering design factors when developing energy harvesters for specific applications. Using simulation tools such as COMSOL Multiphysics can aid in the design and optimization process, allowing for a more efficient and effective energy harvester [33].

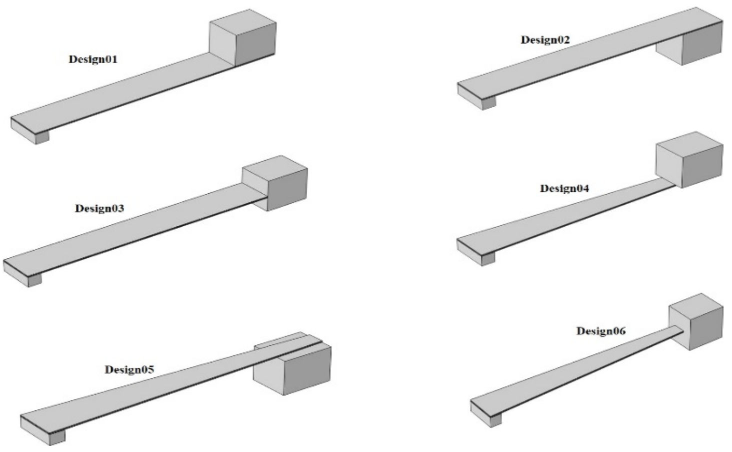


Figure 1. (a) Circuit and Energy Extraction

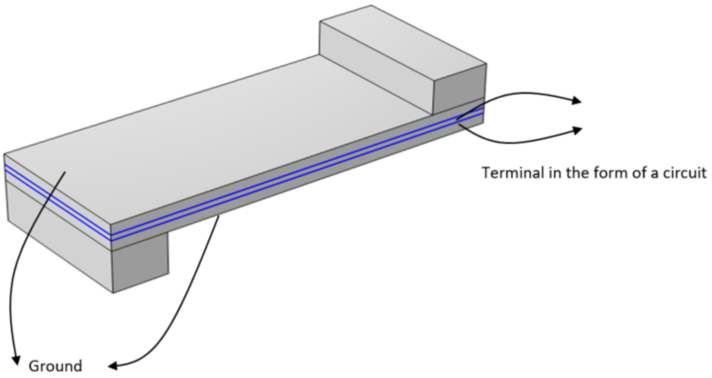


Figure 1. (b) Circuit and Energy Extraction

Table 1. Properties of various designs used

Design No.	Shape I	Details
Design01	Rectangular	The proof mass is located on the upper side of the flexible end of the rectangular cantilever.
Design02	Rectangular	The cantilever has a rectangular shape and a proof mass attached to the base of its flexible end.
Design03	Rectangular	The cantilever has a rectangular shape with a proof mass affixed in the middle rather than the ends.
Design04	Trapezoidal	The cantilever has a trapezoidal shape and a proof mass attached to its upper, flexible end.
Design05	Trapezoidal	The proof mass is located at the base of the trapezoidal cantilever.
Design06	Trapezoidal	The proof mass is fastened to the center of the flexible end of the trapezoidal cantilever.

Table 2. Boundary conditions & device dimensions

Boundary conditions & device dimensions	
Input applied acceleration	1-2 m/s^2
Loaded resistor	10,000Ohm
Tip mass height	Height(100µm-300µm)
Tip mass length:	Length: (100µm-300µm)

1. Frequency and Voltage Optimization in Piezoelectric Bimorph Cantilever Designs

The six piezoelectric bimorph cantilever designs used for energy harvesting provide fascinating insights into their frequency response and voltage produced, as shown in Figure 2 according to the simulation findings. Design02 outshines it with a slightly higher frequency of 1320 Hz and a voltage of 8.878 mV, whereas design01 displays a frequency of 1260 Hz, producing a voltage of 9.567 mV. Design03 stands out from the rectangular versions with its exceptional performance, including a frequency of 1020 Hz and a voltage of 8.646 mV. While both Designs

04 and 05 display a 1200 Hz frequency, Design 04 produces a higher voltage of 9.679 mV, indicating that the trapezoidal form and the proof mass added on top effectively improve energy harvesting [34]. Alternatively, Design06, which uses a trapezoidal cantilever and a proof mass positioned in the middle, exhibits a lower frequency of 930 Hz while maintaining an admirable voltage of 8.22 mV. The findings highlight how the geometry of the design affects the production of frequency and voltage. Design04 showed the most significant promise for increasing voltage output among the configurations tested.

2. Power Generation Analysis of Piezoelectric Bimorph Cantilever Designs

Additional refinement of the performance characteristics of the six different piezoelectric bimorph cantilever designs is accomplished by measuring the power that is generated, as depicted in Figure 3 On the other hand, design01 (1260 Hz) and design02 (1320 Hz, which is somewhat higher) both produce 0.0046 µW and 0.0039 µW, respectively, regarding the amount of power they produce. A power output of 0.0037 µW is generated by design03 when operating at a frequency of 1020 Hz; this proves that design03 can produce power at a competitive level, even though it has a distinct proof mass positioned in the center of the cantilever. The effectiveness of the trapezoidal design with top-mounted proof mass is shown by the fact that Designs 04 and 05, respectively, have consistent power outputs of 0.0047 µW and 0.0046 µW at 1200 Hz. When operating at 930 Hz, the power output of Design06 is 0.0034 unified watts. These results once again show it that the cantilever form and proof mass location are very critical for successful energy harvesting [18]-[25]. These findings provide more evidence that the patterns in voltage output that have been seen in the past are correct. Design04 stands out as a potential competitor for enhanced energy conversion in applications that are used in the real world because it has greater voltage and power outputs.

3. Consistent Voltage Response to Acceleration in Piezoelectric Bimorph Cantilevers

When the influence of applied acceleration on produced voltage is investigated, it is seen that there is a relationship that is both consistent and linear throughout all six configurations of the piezoelectric bimorph cantilever designs, as shown in Figure 4 (a). The fact that the voltage output rises proportionately with increasing acceleration is evidence of a reaction that may be predicted in response to external mechanical forces. Design04 comes out again, exhibiting higher performance than the other designs. This is something that should be taken into consideration. Specifically, the voltage rise it experiences in reaction to acceleration is more significant. The reliability and predictability of piezoelectric energy harvesting devices are shown by the linear connection that exists between the acceleration and the voltage output. Design04 is a strong competitor for applications that need effective energy conversion amid varying accelerative demands. It is a product that has emerged as a result of the trends that have been observed, which further underscore the significance of design subtleties. Additionally, the outcomes of this research support the hypothesis that a trapezoidal cantilever structure with a proof mass attached on top might boost energy harvesting efficiency. These findings shed insight into how the production of voltage scales with various degrees of acceleration [19]. An examination of the influence of applied acceleration on produced power for the six piezoelectric bimorph cantilever designs revealed a pattern comparable to the one seen for voltage. When the amount of acceleration that is applied is raised, the quantity of power created follows a linear response in each design. The Design 04 design, on the other hand, regularly outperforms the different configurations, demonstrating a more noticeable rise in power production in proportion to the acceleration increase [11]-[26]. Design04 is even more firmly established as a highly efficient solution for power production under various acceleration circumstances due to its constant linear connection. When the top-mounted proof mass is paired with the trapezoidal cantilever design, as shown in Figure 4 (b), it seems to give a significant advantage in terms of mechanical energy harvesting and electrical power conversion capabilities. The findings demonstrate how essential it is to consider every aspect of the design process when developing piezoelectric energy harvesters to ensure that they function as well as possible in a wide variety of dynamic circumstances. When it comes to applications that need power generation that is both efficient and reliable, Design04 is, without a doubt, the way to go [20]-[27].

4. Resistor Value Dynamics and Design Effectiveness in Piezoelectric Energy Harvesting Devices

The investigation into the influence that the values of the input resistor have on the production of voltage has shown an exciting dynamic across all six designs of piezoelectric bimorph cantilevers. For resistor values ranging from 1000 Ω to 9000 Ω, Design01 consistently outperforms the other designs, demonstrating maximum voltage responses. This applies to all resistor values. As the crucial threshold of 9000 Ω approaches, it is seen that Design04's voltage response exceeds that of Design01, suggesting a substantial change in performance. After this point, Design04 continuously maintains a larger voltage output than Design01, no matter how much the resistor values grow. When it comes to optimizing voltage generation, this transition highlights the complex relationship that exists between resistor values and design effectiveness. As the resistor values go beyond 9k Ω, Design04 appears as the best option, although Design01 exhibits supremacy for smaller resistor values for a more extended period [27]-[28]. Within piezoelectric energy harvesting devices, this nuanced knowledge shows the significance of considering both the design attributes and external influences, such as resistor values, to achieve optimum performance throughout a wide range of operating situations. Various patterns have occurred in the course of the inquiry into the impact of the input resistor's values on the production of power across all six types of piezoelectric bimorph cantilevers. Particularly noteworthy is that, in the case of designs 01, 04, and 05, the power first rises as the resistor values escalate, reaching a maximum of around 3kΩ, then it begins to decrease [31]. According to this tendency, a range of resistor values is ideal for these specific designs, which maximizes the amount of power produced. On the other hand, designs 02, 03, and 06 have a distinct Performance, with power constantly rising as resistor values increase throughout the board. However, despite this tendency, these designs continually exhibit lower power outputs when compared to designs 01, 04, and 05. This is the case, which can be seen in Figure 5(a). Concerning design 04, as shown in Figure 5(b), it is worth mentioning that when the resistor values exceed 9kΩ, the power output of design 04 surpasses that of design 01, showing a significant advantage in terms of power production efficiency at higher resistor circumstances. This result is particularly noteworthy. The dynamic link between resistor levels and power production is shown by this change, which occurs across various design configurations. In contrast, design 01 exhibits the maximum power production among all designs when the resistor value is 3kΩ, which is the point at which power reaches its peak. This analysis highlights the complexity of optimizing power generation in piezoelectric energy harvesting systems. It emphasizes the importance of considering both design-specific characteristics and external factors, such as resistor values, to maximize performance across various operating conditions. Examples of these factors include resistor values [21]-[29].

5. Piezoelectric Power and Voltage Varying with Tip Mass Length

As shown in Figure 6, Throughout the whole range of 100 *μm* to 300 *μm*, a consistent pattern is shown in the simulation that studies the impact of increasing the tip mass's length on the device's frequency and voltage amplitudes. The device's frequency decreases as the tip mass length increases, but the voltage amplitude increases simultaneously. Mechanical considerations about the effect of tip mass extension on cantilever resonant Performance are brought to light because frequency is inversely proportional to tip mass length. Increasing the tip mass from short to long improves energy conversion efficiency, as shown by the increase in voltage amplitude that was noticed simultaneously. The larger tip mass very certainly causes this phenomenon by increasing mechanical deflection. An enhanced piezoelectric reaction causes the subsequent generation of voltage.

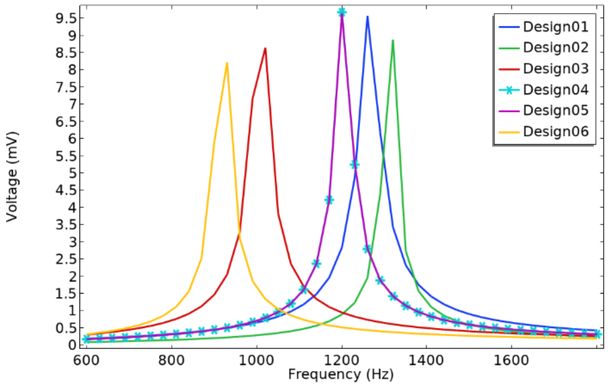
The device's power output also follows a similar trend, increasing in direct correlation with the change in tip mass length. Increasing the bulk of the tip increases the device's energy-collecting capacity by allowing more significant mechanical movement and, therefore, electrical output. This relationship gives more evidence for this hypothesis. These findings provide light on how vital tip mass length is as a design parameter when trying to maximize the efficiency of piezoelectric energy harvesting systems. With this parameter, engineers may fine-tune the device's resonance frequency to suit a particular application's requirements while optimizing the device's efficiency in converting energy [11]-[30].

6. Piezoelectric Power and Voltage Varying with Tip Mass Height

Like that seen for tip mass length, the simulation examining the effects of increasing the tip mass height on the voltage amplitudes and device frequencies revealed that. Within the 100 μm to 300 μm measurement region, increasing the tip mass height causes a decrease in device frequency while simultaneously expanding the voltage amplitudes. Since there is a constant inverse relationship between the height of the tip and frequency, the mechanical effect of the mass expansion of the tip further emphasizes the device's resonant nature. Because the cantilever structure is subject to increasing mechanical strain as the tip mass rises in height, the structure's natural frequency decreases. Simultaneously, increasing mechanical deflection may explain why taller tip masses are linked to more significant voltage amplitudes, suggesting an enhanced piezoelectric response[1].The mechanical displacement improvement improves the device's energy conversion efficiency, which increases the voltage-producing capabilities. As the tip mass rises in height, so does the device's power output [22]-[23]. This pattern illustrates how the height of the tip mass plays a crucial role in optimizing the device's energy-collecting potential. Because it permits the optimization of the resonance frequency and the efficiency of energy conversion, the findings demonstrate that the height of the tip mass is an essential design parameter for piezoelectric energy harvesting systems. Engineers may adjust the device's tip mass length and height to suit user requirements for best performance in a specific application.

RESULT AND DISCUSSION

There are several essential reasons why Design 04 was successful. To start with, the cantilever's trapezoidal shape increases the energy conversion efficiency by introducing a non-uniform stress distribution, boosting the piezoelectric effect. In addition, by positioning the proof mass at the cantilever's upper end, the length of the lever arm is maximized, which increases the mechanical strain on the piezoelectric material and, in turn, the electrical output. In addition, Design 04 showed incredible adaptability by functioning outstandingly over a wide variety of resistance values, especially in cases when the resistance was more than 9 kilo-ohms. The design's resilience and its compatibility with many real-world uses are highlighted by its flexibility. These results confirm that Design 04 works as intended and highlight how vital design optimization is for the future of piezoelectric energy harvesting. The findings of this work may help scientists and engineers improve piezoelectric energy harvesting devices for use in a wide variety of applications, from wearable electronics to infrastructure health monitoring.



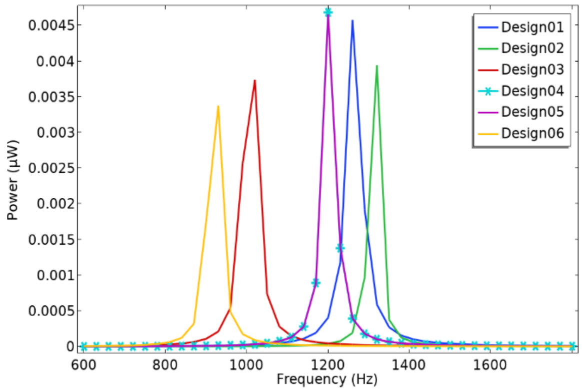


Figure 2. Frequency vs generated voltage D_{1-6} **Figure 3.** Frequency vs generated power for D_{1-6}

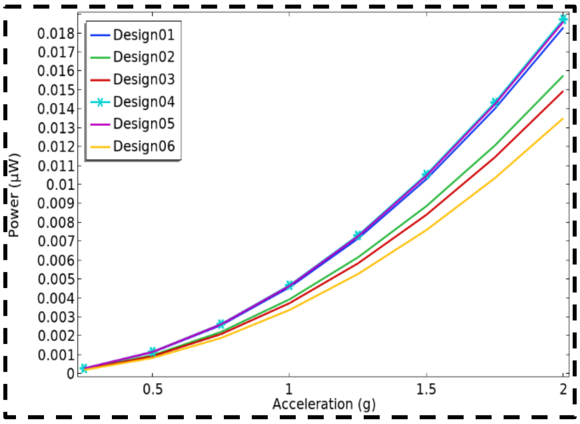


Figure 4 (a). Generated power by increasing the acceleration in D1-D6

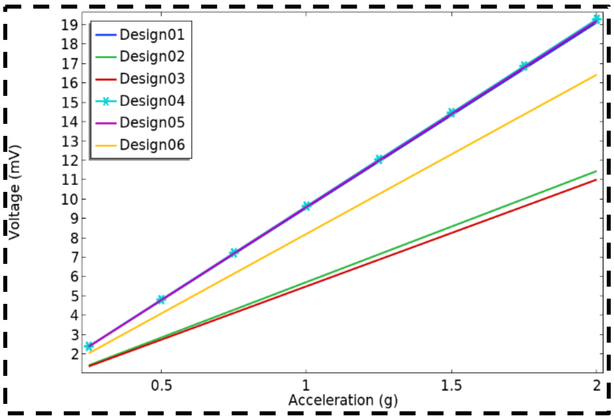


Figure 4 (b). Generated voltage by increasing the acceleration in D1-D6

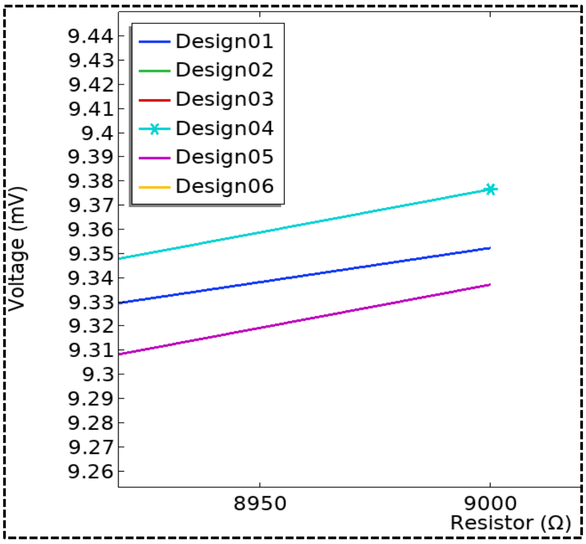


Figure 5(a). Generated voltage by varying the resistance in D1-D6

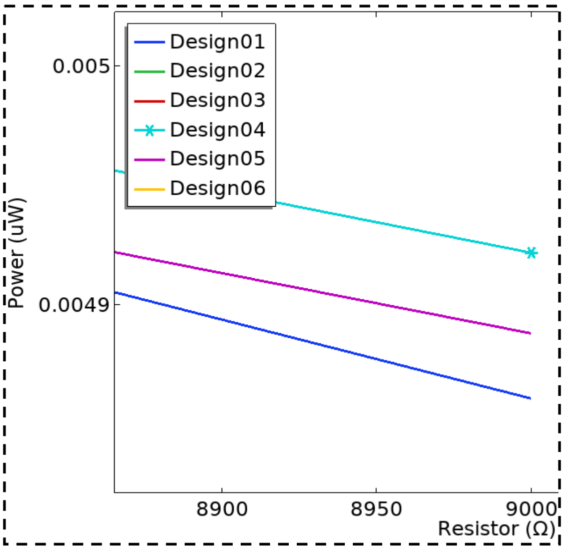


Figure 5(b). Generated Power by varying the resistance in D1-D6

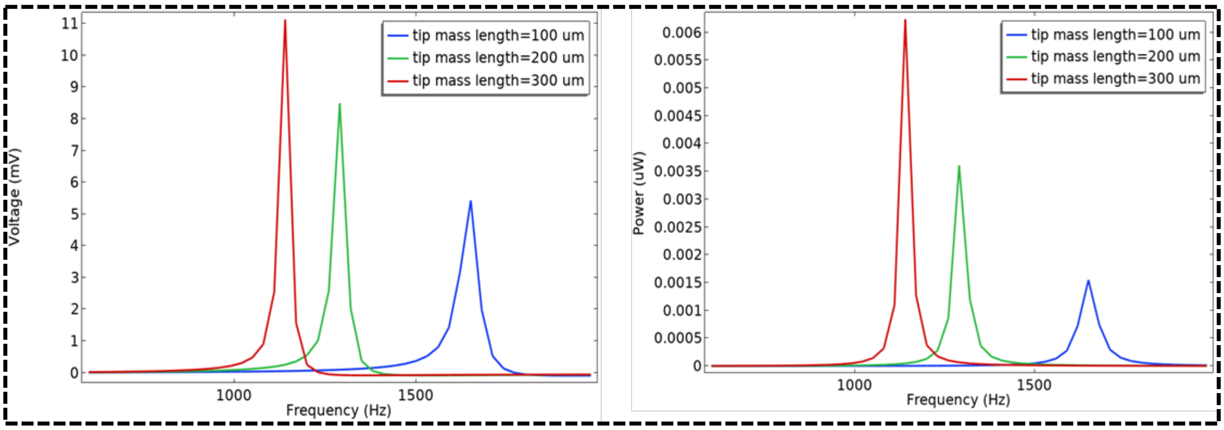


Figure 6. Generated Power and voltage by varying the Tip mass length (100μm-300μm)

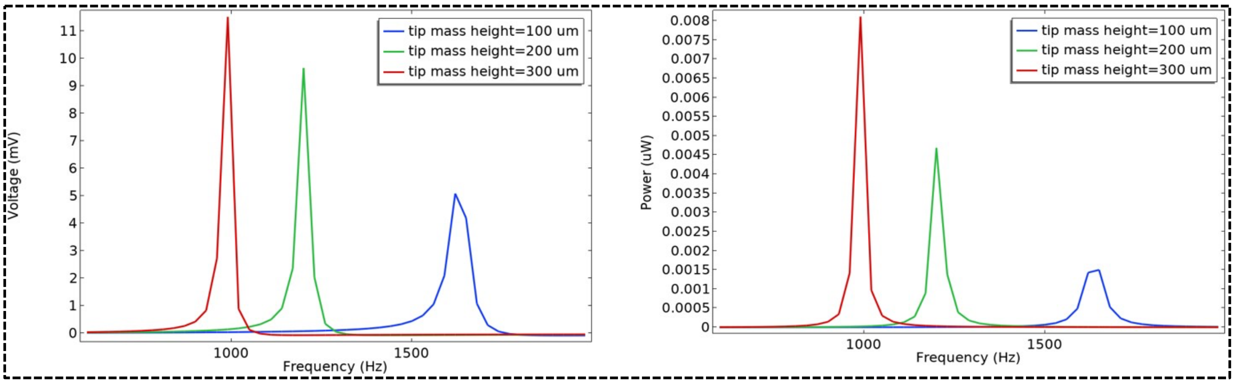


Figure 7. Generated Power and voltage by varying the Tip mass height (100μm-300μm)

CONCLUSION

This study demonstrates that PZT-based MEMS piezoelectric energy harvesters can generate significant power when designed with appropriate resonant structures. Piezoelectric energy harvesting is an exciting new development in the renewable energy sector because it takes advantage of materials' inherent properties to produce electric charges when subjected to mechanical stress. Using COMSOL Multiphysics, this research painstakingly investigated six different designs of piezoelectric bimorph cantilevers, each with its configuration and proof mass locations. The goal was to find the best design for energy collecting in different situations. Design 04 stood out among the many assessed designs with its outstanding voltage and power-generating capabilities. Using a trapezoidal cantilever shape and strategically placing the proof mass at the upper end of the flexible structure were two key components that contributed to this design's exceptional performance. With this setup, mechanical deformation was more efficiently accomplished, leading to a more excellent conversion of mechanical energy into electrical energy. By leveraging numerical simulations, engineers can evaluate different configurations, considering factors like material properties, geometrical variations, and excitation conditions. This approach aids in the development of innovative designs tailored for specific applications, enhancing the overall efficiency of energy harvesting systems. Continued research in this field contributes to advancing renewable energy technologies, paving the way for more sustainable power generation solutions.

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