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Design of Energy Harvester using Piezoelectric Material

Amrutha K R[1], Praveen Kumar M S[2]

Student, Department of Electronics and Communication, JSS S&TU, Mysuru, India[1]

Assistant Professor, Department of Electronics and Communication, JSS S&TU, Mysuru, India[2]

Abstract: This paper offers an extensive examination of energy harvesting approaches, with a special focus on the utilization of piezoelectric energy harvesting. This method capitalizes on the unique capability of specific materials to produce an electric field when subjected to mechanical forces, a phenomenon termed the direct piezoelectric effect. Piezoelectric transducers are available in various forms and materials, rendering them adaptable for a wide array of applications. In addition to this, the paper delves into the significance of modeling the behavior of piezoelectric materials in both the time and frequency domains to enhance their utility. Additionally, it investigates several circuit configurations designed to optimize the efficiency of energy harvesting from piezoelectric devices.

Keywords: Piezoelectric harvesting, Direct piezoelectric effect, Transducer, Efficiency enhancement, Time and Frequency Modelling.

I. INTRODUCTION

Piezoelectric energy harvesting has emerged as a pivotal and innovative solution for addressing energy needs in various engineering applications and systems. It plays a crucial role in scenarios where traditional power supplies are either not feasible or not preferable. This article's primary objective is to provide readers with an in-depth and comprehensive review of the diverse technologies and methodologies that have been explored and documented in the existing literature.

One of the central themes of this article revolves around piezoelectric energy harvesting tiles. These tiles are at the forefront of research and development in this field, serving as key components for capturing and converting mechanical energy into electrical power. The discussion within this article dives deeply into the multitude of designs and mechanisms employed in these tiles. These designs range from simple to highly sophisticated, each with its own set of advantages and challenges.

Feasibility is another pivotal aspect addressed in this article. It critically evaluates the viability of piezoelectric energy harvesting from both economic and energy-related perspectives. This comprehensive analysis aids in understanding the practicality and sustainability of implementing such systems in real-world applications. Moreover, the article highlights the challenges and obstacles encountered in successfully implementing piezoelectric tiles and provides insights into potential solutions. These challenges encompass a broad spectrum, including material selection, mechanical coupling, and environmental factors. Recognizing these hurdles and exploring ways to overcome them is crucial for advancing the practicality and efficiency of piezoelectric energy harvesting.

II. LITERATURE REVIEW

In this section, we find a compilation of information on various methodologies and algorithms that have been previously developed in the field of energy harvesting. These methods have either been adopted in practical use or have become outdated due to newer discoveries and inventions. Goyal et al. introduced the use of piezoelectric materials for electricity generation, capitalizing on their ability to convert mechanical energy into electrical energy. This approach holds promise for applications such as mobile phone chargers and implantable biomedical devices [1]. Dragon et al. delve into the properties of ferroelectric materials, including ferroelectric thin films and ceramics. They discuss various processes affecting ferroelectric devices and provide insights into topics such as polarization switching, fatigue, and domain-wall displacement [4].

Hwanjoo et al. discuss thermoelectric systems designed to power electronic skin (e-skin) sensors using body heat. They investigate models of the human thermoregulatory system and propose heat sink designs for integration with thermoelectric systems [7]. John et al. explore renewable energy technologies in their book, emphasizing their modern applications and case studies. This resource is valuable for multidisciplinary science and engineering programs, as well as for scientists and engineers seeking a broader understanding of renewable energy [2]. Zhou et al. provide a

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comprehensive review of energy harvesting technologies from the ambient environment for Wireless Sensor Networks (WSNs) [8].
Sukhatme et al. address the potential of renewable energy sources to meet India's future electricity needs. Their analysis suggests that while India's energy demand is substantial, the available renewable energy potential may fall short of meeting these needs [3]. Lines et al. develop the modern theory of ferroelectricity, covering topics such as soft modes, lattice dynamics, and measurement techniques. They also explore related phenomena like pyroelectricity and ferro elasticity [6]. Covaci et al. present a review of energy harvesting methods, with a specific focus on piezoelectric energy harvesting. They emphasize the importance of modeling piezoelectric behavior and also discuss circuits for maximizing energy harvesting efficiency [10].
Marin et al. focus on ZnO nanowire-based generators and the energy harvesting mechanisms underlying their operation. They seek to uncover signal sources that differ from common explanations [5]. Sarker et al. focus on vibration-based Piezoelectric Energy Harvesting Systems (PEHS) and optimization techniques to enhance their performance [9].

III. BLOCK DIAGRAM

The power harvester described here features a piezoelectric bimorph design, anchored at one end with a proof mass attached to the opposite extremity. Embedded within the bimorph is a ground electrode, meticulously positioned to coincide with the neutral plane of the cantilever beam. Additionally, two electrodes are strategically placed on the beam's external surfaces. This configuration ensures that both exterior electrodes induce an equivalent voltage, despite the opposing stress experienced above and below the neutral layer.

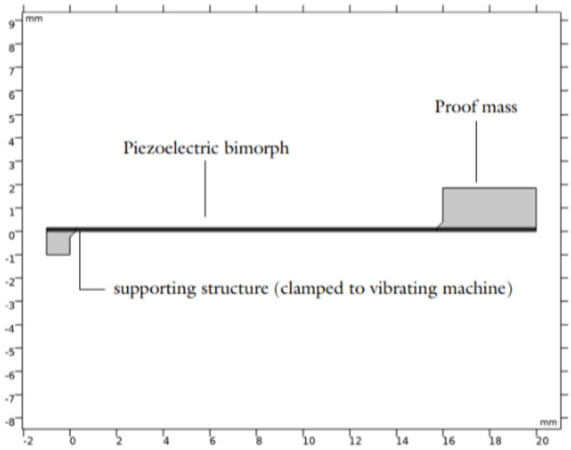

Fig. 1. The piezoelectric bimorph, proof mass, and supporting structure are all visible in the 2D model geometry of the energy harvester.

Fig 1. shows the 2D model. To assess the performance of this energy harvester, it is analyzed within a vibrating reference frame, simulated using COMSOL with a sinusoidal body load. Three critical mechanical analyses are conducted. Firstly, the power output is studied concerning vibration frequency while maintaining a fixed electrical load. Secondly, the relationship between power output and varying electrical loads is explored. Lastly, the analysis demonstrates the linear correlation between DC voltage output and acceleration. These insights into the device's behavior under different conditions are vital for optimizing its performance and practical application in energy harvesting systems.

IV. MATERIAL THEORY

The energy harvester is designed with a piezoelectric bimorph structure, combining a proof mass and strategically placed electrodes for efficient energy conversion. Its clamped-end configuration ensures stable operation in vibrating environments.

A. Material Selection

For energy harvesting, which aims to maximise the conversion of mechanical energy into electrical energy, the selection of a piezoelectric material is essential. This is dependent on a high electromechanical coupling factor, abbreviated "k," where "k" squared represents the material's efficiency in this conversion. For a more precise evaluation, a figure of merit (DFOM) is derived from detailed modeling of a piezoelectric cantilever:

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$$DFOM = \left(\frac{k_{31}^2 \times Q_m}{S_{11}^E}\right)_{on-resonance} \left(\frac{d_{31} \times g_{31}}{\tan\delta}\right)_{off-resonance}$$

…….Eq.1

In this case, the mechanical quality factor is Q_m, the elastic compliance at constant field condition is s_{11}^E, the transversal piezoelectric strain constant is d_{31}, the transversal piezoelectric voltage constant is g_{31}, and the dielectric loss factor is tan. K_{31} stands for the transversal electromechanical coupling factor. A strong coupling factor k_{31} and a sharp mechanical quality factor Q_m are necessary under resonance situations for greater output power, however they cause a narrower bandwidth.

Energy harvesters typically work best at their resonance frequency. However, aligning the resonance frequency with the input frequency is not always possible. In off-resonance situations, the selection criterion becomes the "d · g" parameter, where the relationship between d · g and k2 is expressed as:

$$k_{31}^2 = \left(\frac{d_{31}^2}{S_{31}^E - \epsilon_{33}^T}\right) = \left(\frac{d_{31} \cdot g_{31}}{S_{31}^E}\right)$$

……Eq(2)

Enhancing the "d · g" coefficient in conventional piezoelectric ceramics through composition adjustments is challenging, as increasing the piezoelectric constant (d) often leads to a significant rise in dielectric permittivity (ε), resulting in a trade-off between "d" and "g." However, recent breakthroughs like the template grain growth (TGG) technique have enabled the production of textured relaxor- piezoelectric ceramics with substantial "d · g," along with enhanced piezoelectric response in lead-free materials.

B. Material Options

Ceramics, single crystals, polymers, and composites are the four basic types of piezoelectric materials for energy harvesting. Due to their low cost, strong piezoelectric characteristics, and simplicity of integration, ceramics—in particular PZT ceramics like PZT-5H (APC 855) and PZT-5A (APC 850—are often employed. Lower-frequency functioning necessitates bigger elements or greater excitation levels, although these ceramics operate effectively at frequencies of 50 Hz or above.

Piezoelectric polymer-based harvesters are adaptable and appropriate for lower input frequencies (10 Hz) or when there are higher excitation amplitudes present. But because of their low coupling coefficients, they frequently provide lower power outputs, ranging from microwatts to nanowatts. PZT-polymer composites can be made to have more mechanical strain tolerance by adding polymers, but the power output won't be noticeably improved.

Piezoelectric single crystal-based harvesters have a poor mechanical strength and a high cost, making them infrequently employed. Early prototypes only produced a few milliwatts of power as of 2015. However, they provide improved power density.

V. DESIGN AND METHODOLOGY

In particular for collecting mechanical vibrations, cantilever designs are generally preferred in piezoelectric energy harvesters. They provide a simple and affordable production procedure, excel at producing significant mechanical strain during vibration in the piezoelectric material. In contrast to other vibration modes of the piezoelectric element, the basic bending mode of a cantilever works at a significantly lower frequency.

The majority of piezoelectric energy harvesting devices use a cantilever construction and either a unimorph design (one layer of piezoelectric material bonded to a non-piezoelectric layer) or a bimorph design (two layers of piezoelectric material connected to a non-piezoelectric layer). Due to their capacity to double energy production without considerably expanding the device's size, bimorph piezoelectric cantilevers are often used in research. A proof mass can be fastened to the free end of the cantilever to further reduce its resonance frequency, with the power output being exactly proportional to the proof mass's mass. As an alternative, a zigzag cantilever with less stiffness can be utilised to reduce the structure's resonance frequency.

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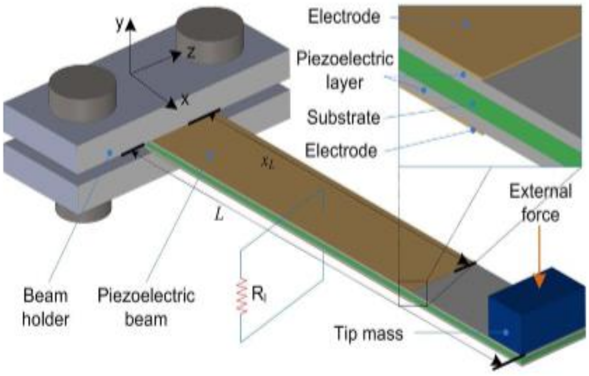

Fig 2. Piezoelectric Substrate

Off-resonance energy harvesters like cymbal transducers and piezoelectric stacks offer an alternative architecture. Cymbal transducers, with force amplification, can enhance power output. Piezoelectric stacks use the d33 mode for higher efficiency but have high stiffness, placing their natural frequency above typical environmental vibrations (10 Hz - 100 Hz). While less sensitive to stress, they withstand greater mechanical loads than cantilever harvesters, yielding higher energy output. Piezoelectric energy harvesting spans different scales: macro/mesoscale (manual assembly), MEMS scale (photolithography techniques), and nanoscale (piezoelectric nanowires). Size depends on factors like weight, dimensions, fabrication, and applications.

A. Working Procedure:

Some crystalline materials with non-centrosymmetric structures have a property called piezoelectricity. Piezoelectric materials use the direct piezoelectric effect in vibration energy harvesting to transform mechanical strain into electrical charge or voltage. Combining intrinsic and extrinsic elements can have an impact on a piezoelectric energy harvester's power output. The frequency constant of the piezoelectric component, the mechanical and piezoelectric characteristics of the material, as well as how temperature and stress affect these qualities, are intrinsic variables. The frequency of the input vibration, the acceleration of the host or base structure, and the intensity of the excitation are all examples of extrinsic influences. Adjustments may be made to the energy harvester's operating frequency range and power output due to the interplay between the mechanical design and material qualities.

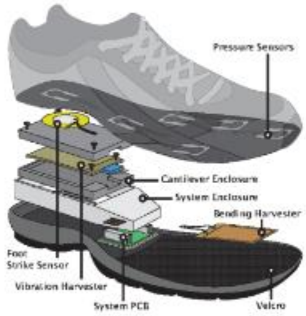

Fig 3. Expanded view of the shoe system and all integrated components

The operating frequency has a considerable impact on the effectiveness and power density of a piezoelectric vibration energy harvester. Due to the piezoelectric material's peak power generating capability occurring at the electromechanical resonance frequency, this relationship results. As frequency increases, the potential output power of an energy harvesting device diminishes (proportional to 1/f, where f is the frequency of the fundamental vibration mode), making it imperative to focus on the low-frequency fundamental mode while designing the device. Because of these weight and size restrictions, it is difficult to employ ceramics to obtain the appropriate fundamental frequency when dealing with lower-frequency vibration sources.

VI. RESULT AND CONCLUSION

The results reveal various key parameters when the energy harvester is subjected to sinusoidal acceleration: input mechanical power, harvested power and the peak voltage induced. These measurements are presented across a range of frequencies. The electrical load connected to the system is 12 kΩ. Notably, the system's response exhibits a prominent

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peak at 76 Hz, which closely aligns with the calculated resonant frequency of the cantilever, determined separately through eigenfrequency analysis, and found to be 73 Hz.

A. Response of PZT-5A Material:

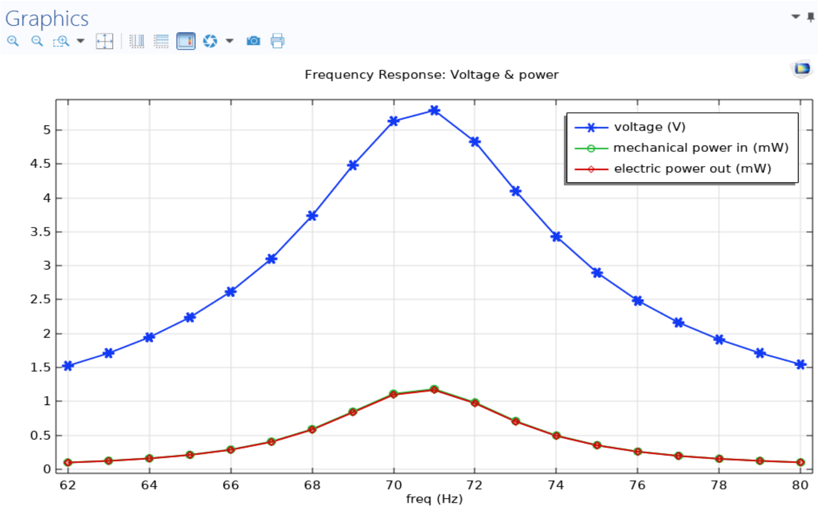

Fig 4. Graph depicting input mechanical power, harvested power (mW), and peak voltage (V) vs. excitation frequency.

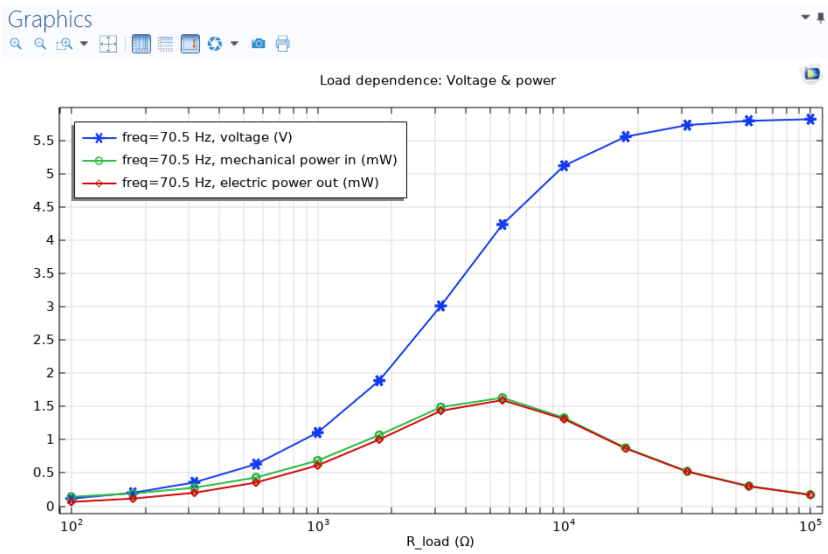

Fig 5. Power harvested vs. electrical load resistance at 1 g acceleration, oscillating at 75.5Hz (PZT-5A).

In Figure 5, the harvested power from the device is plotted against the electrical load resistance while the system experiences an acceleration of 1 g at a frequency of 75.5 Hz. The graph highlights that the maximum energy harvested is achieved when the electrical load resistance is set at 6 kΩ.

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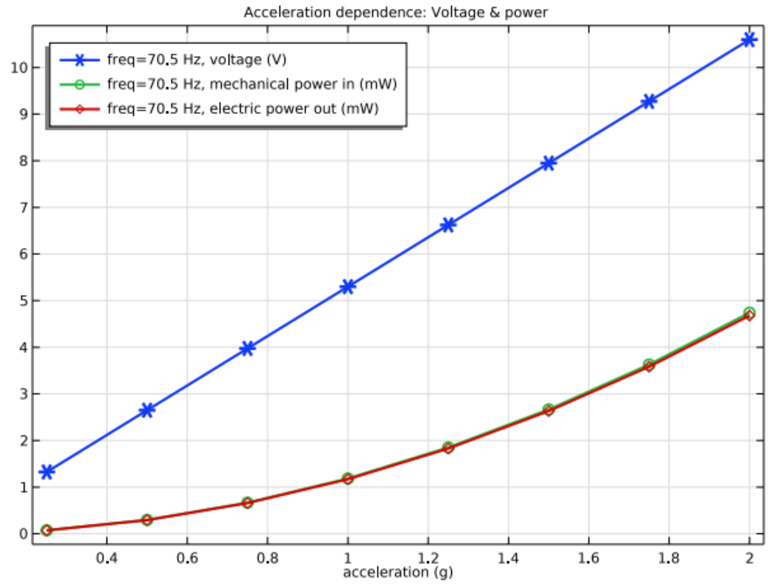

Fig 6. DC voltage and power output vs. mechanical acceleration at 75.5Hz with a 12 kΩ load for PZT-5A.

In Figure 6, The graph shows DC voltage and power output with load resistance at 75.5 Hz, 1 g acceleration, and a 12 kΩ load for PVDF. Voltage increases linearly with load, while power output grows quadratically.

B. Response of PVDF Material:

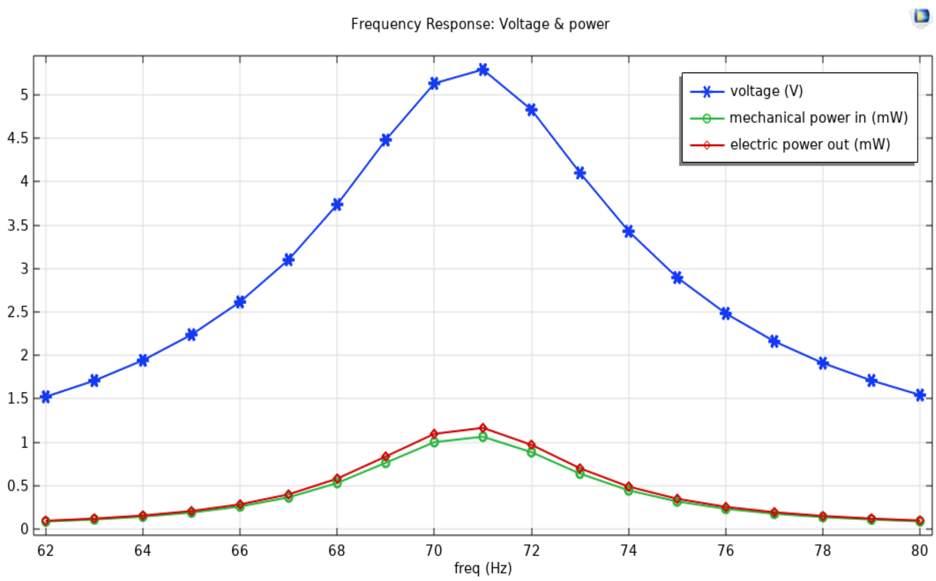

Fig 7. Input mechanical power, harvested power (mW), and peak voltage (V) vs. excitation frequency for PDVF with a 12 kΩ load and 1 g acceleration.

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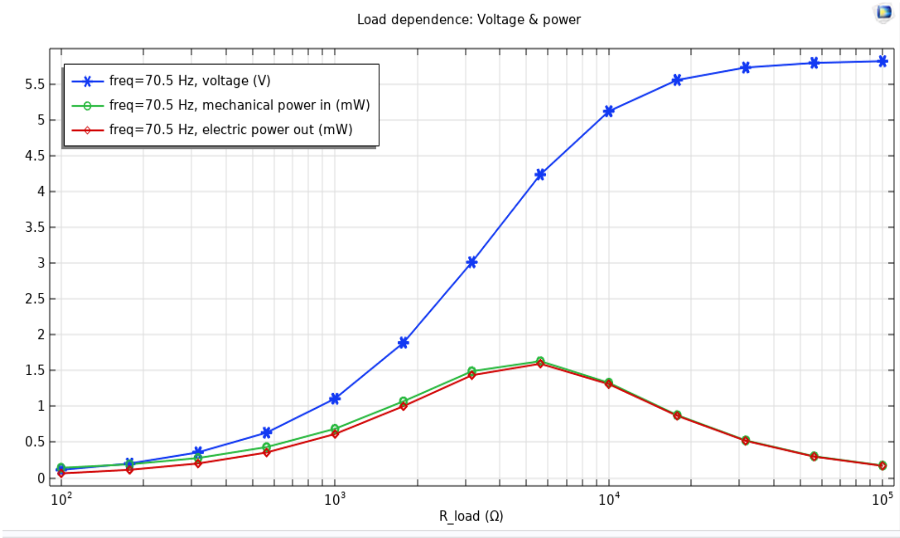

Fig 8. Power harvested vs. electrical load resistance for PVDF at 1 g acceleration and 75.5 Hz oscillation frequency.

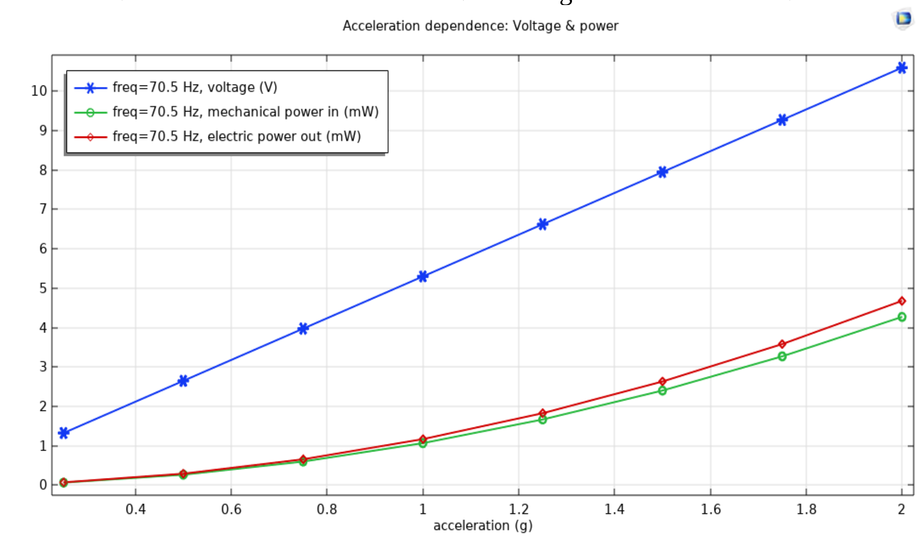

Fig 9. DC voltage and power output vs. acceleration for PVDF at 75.5Hz with a 12 kΩ load.

C. Comparison Table:

Material Type	Peak to peak(u/w)	Frequency(Hz)	Excitation(Acceleration of force or pressure)
PVDF	2	2	0.1 or 0.2 G
	0.0005	2	3-point bending at 3N
	610	3	Wind speed of 4m/s
	2.75	104	1G
PZT	47	1	Vibration at Piezo beams.
	265	1	900N
	2000	20	1N

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VII. CONCLUSION

This paper presents a theoretical model for energy harvesting using piezoelectric materials, highlighting their potential as a cleaner energy source for lighting systems and various devices. With fossil fuels depleting rapidly and causing environmental issues, alternative energy sources like solar, wind, and wave energy have gained popularity. This article focuses on the use of piezoelectric materials to generate electricity, leveraging their ability to convert mechanical energy into electrical energy. The applications range from powering small electronics like mobile phone chargers to implantable biomedical devices. Over the past decade, numerous papers have explored this topic, and this article aims to introduce the subject to students by drawing from existing literature. It not only delves into the underlying principles but also discusses energy harvesting from airport runways and roadways, power generation from shoe-mounted devices, and self-powered nanowire devices.

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