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Numerical Simulation of Magnetoelectric Composite for Power Supply of Small Biomedical Devices

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Abstracts: This paper introduces a comparative numerical modeling and simulation study of a smart composite material combining piezoelectric ceramics Terfenol-D/GFRP/PZT-5H and Terfenol-D/PZT-5H. The remarkable combination of high output voltage coefficients and substantial power output positions this composite as an ideal candidate for energy transduction applications, particularly in wireless power devices within the field of biomedical applications. Additionally, we explored the potential of PZT-5A to evaluate the feasibility of modeling both piezoelectric and magnetostrictive self-sensing responses under the influence of applied stress. This numerical investigation was complemented by a series of mechanical tests aimed at characterizing the piezoelectric and magnetostrictive responses, as well as the material's mechanical strength.The results obtained demonstrate the successful accomplishment of active vibration control through the development of a smart self-sensing composite material. This composite harnesses the piezoelectric properties of PZT-5A ceramics and the magnetostrictive properties of Terfenol-D. The remarkable combination of a high output voltage coefficient and substantial power output positions this composite as an exceptional candidate for energy transduction applications, particularly in the realm of biomedical devices requiring wireless power. Specifically, Terfenol-D/GFRP/PZT-5H composite materials show promise for enhancing wireless powering solutions in biomedical applications

Keywords: Piezoelectric, Magnetostrictive, Terfenol-D, PZT-5A

1. INTRODUCTION

Currently, the adoption of wireless technologies by contemporary digital nomads has attracted considerable interest on a global scale within the scientific community. This interest has led to the emergence of the concept known as the "Internet of Things" (IoT), which focuses on the idea of monitoring and controlling identifiable objects via the Internet. To bring this vision to life, it is crucial to create embedded micro-systems that consist of wireless sensor nodes (WSN). However, a significant challenge that needs to be addressed is the high battery consumption observed in many power-dependent sensors.

A significant challenge revolves around the need to replace or recharge batteries due to their limited lifespan, compounded by the use of environmentally harmful materials. To address this issue and reduce the overuse of pollutants while ensuring energy independence, it becomes highly desirable to power wireless sensors through energy harvesting techniques. These techniques harness ambient energy sources inadvertently introduced or utilize wireless energy transmission, as explored in this study. This presents opportunities for the development of self-powered or wirelessly powered low-power electronic devices, with the potential to bring about transformative changes in our society. For instance, in the healthcare sector, there is a growing interest in the creation of self-powered or wirelessly powered implantable sensors. These sensors are crucial for remote postoperative monitoring, such as after orthopedic or vascular surgeries, and for providing real-time health status updates for vulnerable patient populations, a development of paramount importance. [1]

In the field of biomedical micro-systems, the most commonly proposed and investigated approaches for energy transmission revolve around transducers that primarily utilize either acoustic energy through the use of piezoelectric materials or electromagnetic energy relying on inductive coupling between coils or RF transmission between antennas. However, the utilization of acoustic energy is limited by the necessity for physical contact between the body and the ultrasonic transmitter in use.

Excellent energy conversion between the magnetic and electric fields has been shown via strong strain-mediated magnetoelectric (ME) coupling in magnetic/electric heterostructures. [2,3]

This underscores the substantial potential for practical applications, including the development of sensors and adaptable RF/microwave devices. The magnetoelectric coupling effect primarily stems from the combined influence of the piezoelectric and magnetostrictive properties inherent in the piezoelectric and piezomagnetic phases, respectively. [4,5]

In recent years, there has been significant progress in the development of intelligent self-sensing composites that leverage the synergy between magnetostrictive and piezoelectric materials. This advancement has paved the way for maintenance-free and battery-independent applications. Furthermore, the utilization of energy harvesting technologies, employing magnetostrictive/piezoelectric materials with robust mechanical properties, has proven to be highly effective in converting alternating magnetic energy from environmental vibrations or mechanical loads into electrical energy.

The capacity for magnetoelectric conversion in magnetoelectric components is primarily contingent on the properties of magnetostrictive and piezoelectric materials. The magnetoelectric effect (ME) is a composite phenomenon that occurs within the ferroelectric phase and ferromagnetic phase, each characterized by piezoelectric and magnetostrictive effects, respectively. These phases are interconnected through their elastic responses, facilitating the magnetoelectric effect. [6]

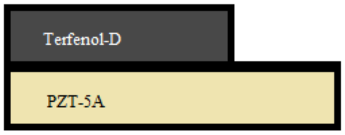
magnetoelectric = magnetostriction × piezoelectricity

ME = magnetic /mechanical × mechanical/ electric (1)

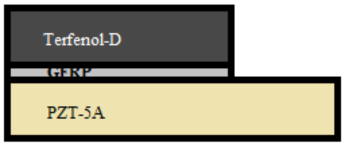
The primary goal of this paper is to create and assess smart composites composed of two magnetoelectric components. In this study, Terfenol-D/GFRP/PZT materials have been structured into a block sandwich configuration, resulting in the development of an intelligent self-sensing fiber-reinforced composite.

2.Self-Sensing Composite FEA:

A 3D simulation model of the composite, comprising GFRP/magnetostrictive layer/piezoelectric layer, was constructed using COMSOL Multiphysics software version 6. The model was specifically designed for a composite structure consisting of one GFRP layer, one Terfenol-D layer, and one PZT-5A layer. Each of these layers had uniform dimensions, measuring 14 mm in length, 10 mm in width, and 1 mm in thickness for both the Terfenol-D and PZT-5A layers, while the GFRP layer had a thickness of 35 µm. Each layer was assigned its unique material properties, as illustrated in Figure 1. The materials employed in this system, along with their respective properties, are detailed in Table 1.



a) ME composite of PZT-5A/ Terfenol-D



b) ME composite of PZT-5A/ GFRP /Terfenol-D

Fig 1: The studied Model geometry of the energy harvester magnetoelectric (ME) structure.

Table 1 Properties of materials used on the COMSOL Multiphysics6.0 model.

PROPERTY	UNIT	TERFENOL-D	PZT-5A	GFRP
DENSITY	kg/m3	7900	7750	2440
POISSON'S RATION	-	0.5	0.294	0.20
MODULUS OF ELASTICITY	Gpa	50-90	70	72.4
RELATIVE PERMEABILITY	-	2-10	{919.1, 919.1, 826.6}	1-4.5
ELECTRICAL CONDUCTIVITY	S/m	1.666e-6	10e-15	1.05*10-4
LINEAR MAGNETOSTRICTION	Ppm	800–1200	-	-

FE MODELLING RESULTS AND DISCUSSIONS

In this section, we conduct a finite element analysis of the Terfenol-D/PZT-5A and Terfenol-D/GFRP/PZT-5A configurations. Both static and frequency-domain analyses are performed to gain insights into how different magnetic fields influence the energy conversion process in magnetoelectric components constructed from Terfenol-D alloy magnetostrictive materials.

The finite element model for the Terfenol-D/PZT-5A and Terfenol-D/GFRP/PZT-5A composites, as well as the von **Mises stress within the harvester materials under a base acceleration of 1 m/s², is depicted in Figure 2.**

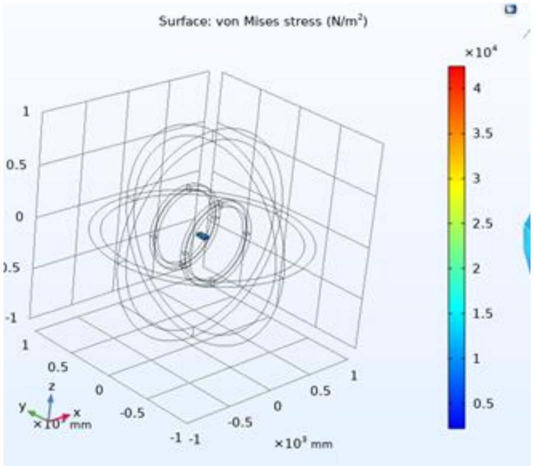


Fig 2: Von Mises stress FEM in harvester materials for base acceleration 1 m s−2

The finite element model provides a detailed illustration of the analysis process for a straightforward cantilever-based magnetoelectric energy harvester. In this analysis, a sinusoidal acceleration is applied to the energy harvester, and the resulting output power is assessed as a function of both frequency and the magnitude of the applied acceleration.

In the COMSOL Multiphysics 6.0 software, this analysis involves establishing a relationship between the strain induced by the applied boundary load and the polarization of the piezoelectric material. This relationship is achieved

$$\varepsilon = s_E\sigma + d^T E \quad \mathbf{2}$$

$$D = d\sigma + \varepsilon_T E \quad \mathbf{3}$$

by solving a set of equations tailored to the specific characteristics of the materials and system under examination.

where ε is the strain applied on the composite sample, σ represents the stress due to the boundary load, E is the electrical field, D is the displacement field, εT is material permittivity, d represents the coupling properties, and SE is the material compliance. The applied boundary load on one end of the composite results in applied stress in three directions with corresponding electrical fields due to the piezoelectric material [7]. The orientation of the piezoelectric layer is also dependent on the defined material properties.

The integration of the PZT-5A layer with the Terfenol-D magnetostrictive layer resulted in the formation of an assembly. To accurately characterize the behavior of the Terfenol-D layer, a solid mechanics model was coupled with magnetic fields to simulate the magnetostrictive response. This coupling allowed for a comprehensive analysis of the material's behavior under varying conditions.

In COMSOL Multiphysics 6.0, the nonlinear behavior of the magnetic field H was approximated and modeled linearly. This linear modeling approach facilitated the establishment of relationships between strain, stress, and magnetic flux, enabling a comprehensive understanding of the interplay between these critical factors in the material's response. [8,9]

$$\frac{\mathrm{dM}}{\mathrm{dt}} = \left(\frac{\partial \mathrm{M}}{\partial \mathrm{H}}\right)\frac{\mathrm{dH}}{\mathrm{dt}} + \left(\frac{\partial \mathrm{M}}{\partial \sigma}\right)\frac{\mathrm{d}\sigma}{\mathrm{dt}} \qquad \mathbf{4}$$

The voltage output versus the frequency for Terfenol-D/ PZT-5A, Terfenol-D /GFRP / PZT-5A are presented in Fig 3.

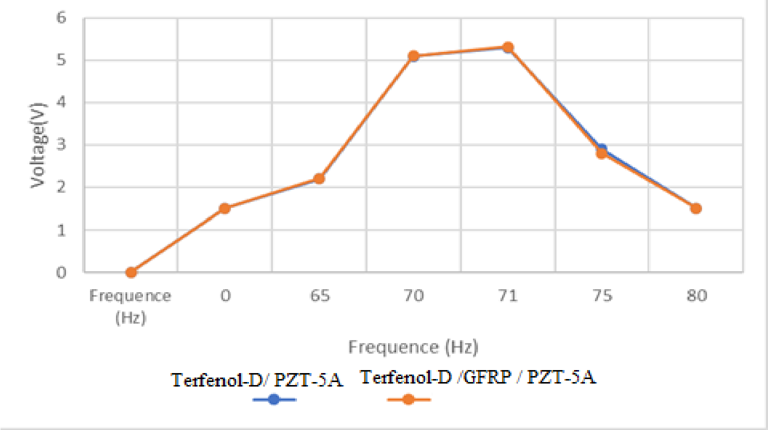


Fig 3: The voltage vs the frequency for Terfenol-D/ PZT-5A, Terfenol-D /GFRP / PZT-5A energy harvester composite.

In the case of the energy harvester composite consisting of magnetostrictive layers made from Terfenol-D alloy, both components exhibit their highest voltage output at 5.5V when subjected to a frequency of 71Hz. For the purpose of studying acceleration, a fixed frequency of 71Hz has been maintained, and a load impedance of 20 kΩ has been applied, as illustrated in Figure 4.a and 4.b for both the Terfenol-D/PZT-5A and Terfenol-D/GFRP/PZT-5A energy harvester composites.

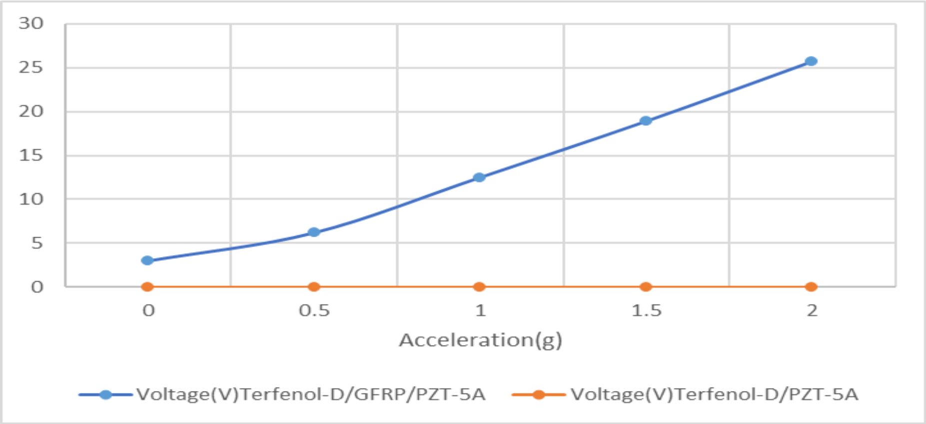


Fig 4.b: Voltage (V) Vs Acceleration (g) at 71Hz.

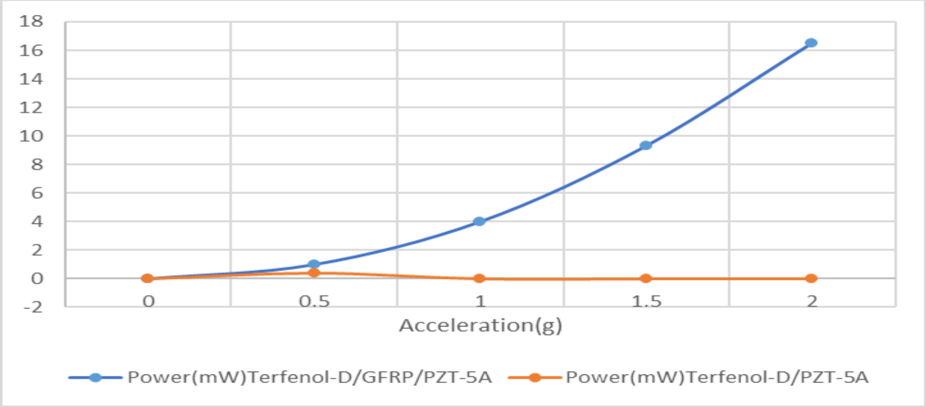


Fig 4.b: Power (mW) Vs Acceleration (g) at 71Hz.

The simulation results reveal significant differences in the voltage output for the two types of magnetoelectric components made from Terfenol-D alloy, namely the Terfenol-D/PZT-5A and Terfenol-D/GFRP/PZT-5A energy harvester composites, when subjected to an acceleration of 2 m/s^2.

For the Terfenol-D/GFRP/PZT-5A energy harvester composite, the voltage increases from an initial value of 0V to a substantial 25V at 2 $m/s^2$for a maximum power of 15.8 mW.

In contrast, the Terfenol-D/PZT-5A energy harvester composite exhibits a much lower increase in voltage, rising only from 0V to 0.002V at the same acceleration of 2 m/s^2.

These simulation outcomes provide valuable insights into the magnetoelectric characteristics of these two distinct magnetoelectric components constructed from Terfenol-D/PZT-5A and Terfenol-D/GFRP/PZT-5A, which can serve as essential guidelines for the design of magnetoelectric energy harvesters.

CONCLUSION

In this paper, we developed a comprehensive magnetodielectric model using Comsol Multiphysics 6.0, which effectively combines both magnetostrictive and piezoelectric elements. Our research showcases the successful implementation of active vibration control through the utilization of a Terfenol-D/GFRP/PZT-5A trilayer composite.

Our model underwent rigorous validation to ensure its accuracy and reliability. We found that the composite's piezoelectric characteristics arise from the dispersion of PZT-5A, while its magnetostrictive properties stem from the presence of Terfenol-D within the interior of the laminate. This underscores the pivotal role of magnetostrictive materials in achieving active vibration control.

Furthermore, our investigation revealed that the thin-profile harvester produces a notably high-power output. This makes it an attractive choice as a smart composite material with promising applications in the fields of microelectronics and sensor technology.

Notably, our research demonstrates that the addition of a GFRP layer between the PZT-5A and Terfenol-D layers leads to a substantial enhancement in the output voltage. This improvement has significant implications for wireless power applications, especially when it comes to powering embedded electronic devices in biomedical contexts.

In summary, our work highlights the potential of smart composite materials in enabling active vibration control, powering microelectronics and sensors, and enhancing wireless energy transmission for critical applications in the biomedical field.

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