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Energy harvesting from walking vibration using a piezoelectric harvester contacting nonlinear supports

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ABSTRACT

In recent years, there has been a growing interest in harnessing environmental energy resources, particularly mechanical vibrations, to power low-energy electrical devices like wireless sensors. Among these energy sources, the movement of the human body stands out. This paper delves into the realm of piezoelectric energy harvesting using the mechanical energy generated by foot acceleration during movement. The energy harvesting mechanism revolves around a nonlinear piezoelectric harvester, featuring a cantilever beam equipped with two piezoelectric patches on opposite sides and supported by curved surfaces. To model the foot's motion, measured foot acceleration is applied as a base excitation to the harvester. Subsequently, a finite element model is developed using the commercial software Ansys, encompassing the entire system, which includes the cantilever beam, piezoelectric patches, supports, and electrical resistance. The culmination of the work involves designing, fabricating, and testing a model. The experimental results are compared with those obtained from the finite element model. A strong correlation is evident between the measured data and the outcomes generated by the finite element analysis.

1. Introduction

Over the past decade, the field of vibration-based energy harvesting using piezoelectric materials has captured significant attention across various research disciplines. This approach holds great promise as a solution for powering self-sufficient wireless sensors. However, traditional single-degree-of-freedom vibration energy harvester models, typically comprising a proof mass and a cantilever beam with piezoelectric patches, exhibit effectiveness only near resonance. They often fall short when dealing with the majority of environmental vibration sources. Enhancing the functionality of these energy harvesters has thus become a critical challenge in this domain.

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Researchers have explored several techniques to improve energy harvester performance, including resonance tuning methods [1-2], the incorporation of multiple degrees of freedom [3], and introducing nonlinearity into the harvester system [4]. Resonance tuning achieved through adjustments in stiffness via mechanical preload [5-6] or magnetic force [7] has been a common approach. Additionally, nonlinear features have been introduced through mechanisms like energy harvesters with piecewise-linear stiffness using mechanical stoppers [8-10] and bistable energy harvesters utilizing repulsive magnets [11-13].

Nonlinear oscillators, characterized by their resistance to external frequency variations and functionality across a broad frequency range, are often modeled using the Duffing equation. The magnetoelastic system, first introduced by Moon and Holmes [14], comprises a cantilever ferromagnetic beam with two permanent magnets near its free end. Depending on the magnets' distance, the beam can exhibit one, two, or three stable states. Research efforts, such as those by Alper Erturk et al. [12] and Stanton et al. [15], explored the potential of magnetoelastic systems for piezoelectric energy harvesting, demonstrating their superiority over linear counterparts.

Studies have also delved into nonlinear energy harvesting from human body movements. Dagdeviren et al. [16] investigated energy harvesting from natural vibrations of internal organs like the heart, lungs, and diaphragm, showing the viability of piezoelectric magnetoelastic harvesters for practical use in implants. Ylli et al. [17] designed nonlinear energy harvesters based on foot swing and heel impact motions, revealing similar patterns in power outputs despite differing physical principles. Wang et al. [18] focused on optimizing piezo magnetoelastic energy harvesters for electrical resistivity.

Furthermore, Kluger et al. [19] designed a nonlinear energy harvester and explored electromagnetic energy harvesting through foot excitation during walking. Their work showcased how nonlinearity could enhance the robustness of energy harvesting under continuous excitation.

In this study, energy harvesting from the swing motion of the foot during walking is investigated using a nonlinear piezoelectric energy harvester. The system is optimized for electrical resistivity, considering the shape of proposed curved surfaces at different walking speeds. The model is fabricated and tested on a treadmill. The results demonstrate a strong correlation between finite element simulations and measured data, emphasizing the potential of nonlinear energy harvesters in real-world applications.

2. Finite element model of nonlinear harvester

Figure 1 shows a sketch of the system composed of a cantilever beam with two piezoelectric patches and two supports with curved surfaces. The proposed nonlinear energy harvester with curved surfaces in the form of third-degree polynomials is modeled using the commercial software Ansys with piezoelectric layers. A cantilever beam is placed between two curved supports. The origin of the coordinates system is located at the standstill state of the beam. The initial length of the cantilever beam is L. As the beam vibration amplitude increases, the points near the origin touch the support surfaces, and this causes a reduction in the effective length of the beam. The effective length of the beam is a function of the beam's transverse vibration. This introduces a source of nonlinearity to the problem. In general terms, if there is no contact between the cantilever beam and the curved surfaces during the beam vibration, the system's behavior will resemble that of a linear vibration. When the base excitation increases, a contact point between the beam and the curved surfaces is generated during each swing of the beam. Therefore, the free cantilever's length will be shortened, and the cantilever stiffens.

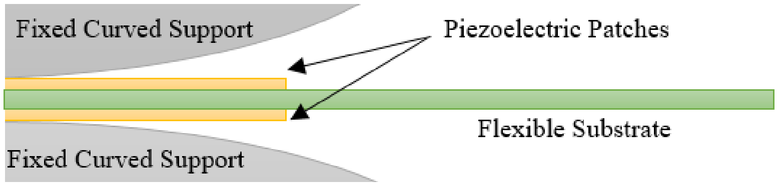

Fig. 1. The nonlinear piezoelectric energy harvester with curved supports

The aim is to compare the functionality of such a harvester with a similar linear energy harvester, i.e., a harvester with no curved supports, in a specific range of frequencies. The elements type of the beam, piezoelectric layers, and electrical resistance are SOLID186, SOLID226, and CIRCUT94, respectively. For modeling the contact between the beam and surfaces, the TARGE170 element is used for the CONT174 elements. The contact elements overlay the beam surfaces, and they are in contact with the support surfaces, which are defined by TARGE170. The model contains 3642 elements and 9,038 nodes.

The left-hand side of the beam is fixed in both models. A base acceleration of 1g*(sin $(2\pi f_1 t)$) m/s^2 was applied to the fixed base of the beam. The amplitude of acceleration was set to 1g, while the frequency of the applied excitation (f_1) was changed from 0 to 40 Hz. The enforced motion method (EMM) was used to apply the base acceleration. The beam and supports are made of steel, and piezoelectric layers are PZT 5H. The material and physical properties of the beam, supports, and piezoelectric layers are listed in Table 1.

The results for the linear and nonlinear systems with the resistance of 1 $M\Omega$ are depicted in Figure 2 for the frequency range of 0 Hz to 40 Hz. As shown in Figure 2, the electric power produced by the nonlinear system is increased significantly compared to the linear system. The maximum generated power for the linear energy harvester is about 68 mW at a frequency of 23.5 Hz. The maximum harvested power from the nonlinear system is about 104 mW at a frequency of 24.5 Hz, about 1.52 times more than the linear harvester. Furthermore, the frequency range of effective energy harvesting is increased for the nonlinear system compared to the linear one.

The main goals of this section were first to model the behavior of the nonlinear harvester with curved supports and second to demonstrate the superiority of the nonlinear harvester under harmonic base excitation.

In the following section, a nonlinear harvester with nonlinear support is employed under human body swing motion.

Table 1. Material properties of the harvester

Beam stiffness (Gpa)	**193**
Piezoelectric stiffness (Gpa)	**63**
Beam density (kg m^{-3})	**7850**
Piezoelectric density (kg m^{-3})	**7500**
Piezoelectric relative permittivity (F m^{-1})	**1436.8**
Vacuum permittivity (F m^{-1})	**8.854*10^{-12}**
Piezoelectric strain constant (C N^{-1})	**-274*10^{-12}**
Beamwidth (mm)	**25**
Beam length (mm)	**160**
Beam thickness (mm)	**0.6**
Piezoelectric width (mm)	**25**
Piezoelectric length (mm)	**160**
Piezoelectric thickness (mm)	**0.15**

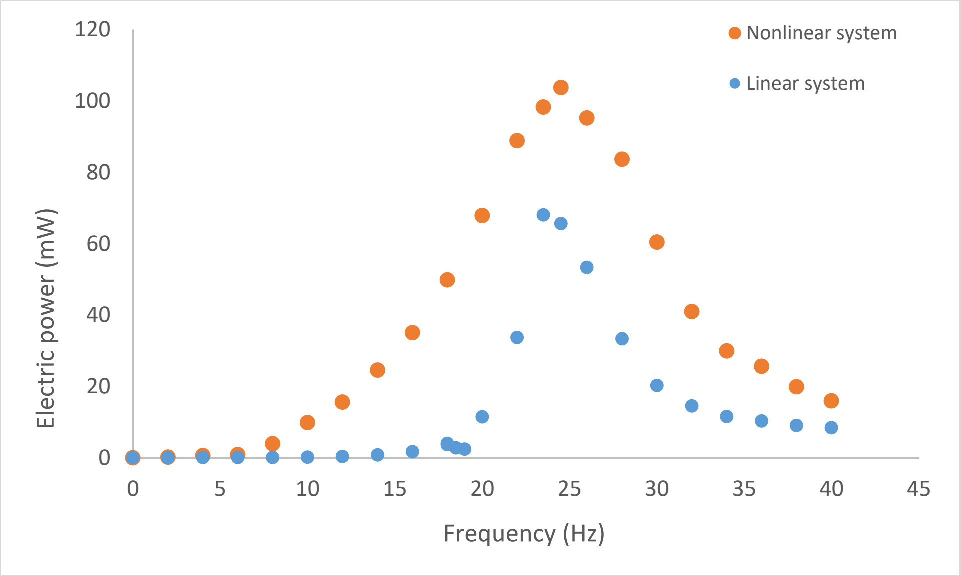

Fig.2. The electric power produced by linear and nonlinear energy harvesters (FEM results)

3. Human body foot swing motion

To utilize the foot swing motion acceleration as the primary input, it was necessary to measure the acceleration experienced by the human foot. At a walking speed of 4 km/h, this acceleration component, perpendicular to the direction of foot movement, was acquired using a portable accelerometer securely attached to an individual's foot. Figure 3 provides a representative graph illustrating the acceleration variation over time. Figure 4 complements this data by presenting the frequency content analysis of the signal obtained in Figure 3. It is essential to note that this measurement process was repeated more than 20 times to ensure accuracy, with the resulting average value being established as the baseline acceleration for the harvester's operation.

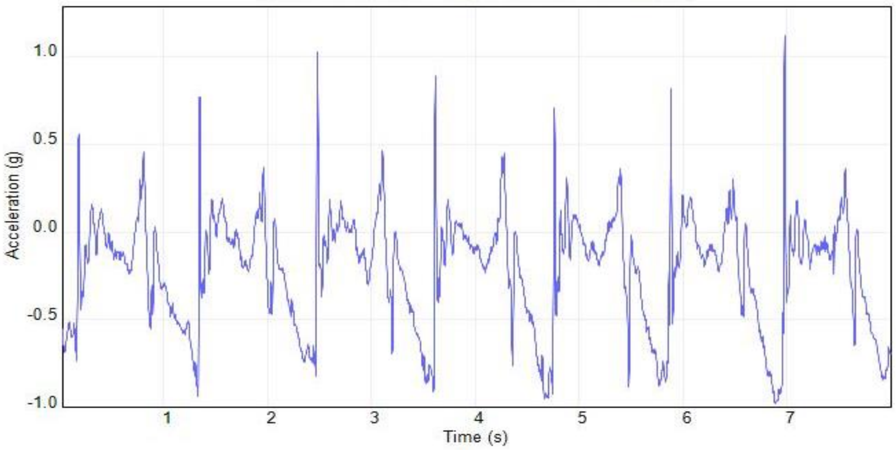

Fig.3. The measured foot acceleration versus time (experimental results)

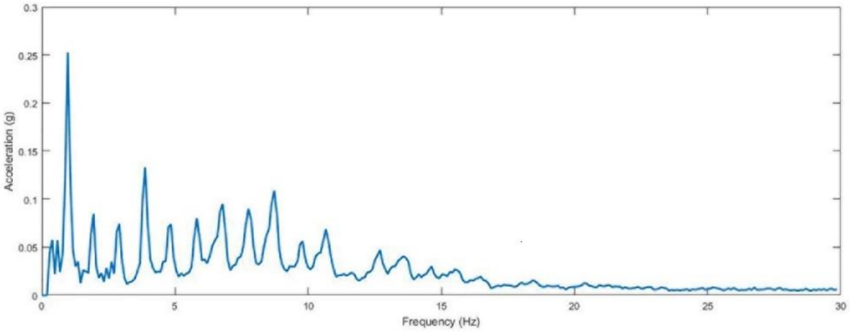

Fig.4. The frequency contents of the measured acceleration (experimental results)

According to Figure 4, the effective frequency of the acceleration signal is under 15 Hz. Therefore, to harvest the energy for such a signal, the energy harvester should have at least a resonance frequency below 15 Hz. Since the harvester shown in Figure 1 has a natural frequency of approximately 25 Hz, the dimension and the total mass of the harvester need to be adjusted. For this purpose, the newly designed system illustrated in Figure 5 is composed of a cantilever beam with two piezoelectric patches near the fixed end on both sides of the beam and two equal masses at the free end of the beam. The geometrical properties of the proposed harvester are shown in Table 2.

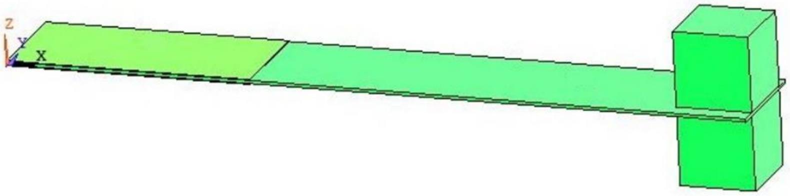

Fig.5. The proposed energy harvester

Table 2. Geometrical properties of the proposed energy harvester under human walking

Beam length (mm)	**140**
Beam thickness (mm)	0.6
Beam width (mm)	20.8
Piezoelectric patch length (mm)	46
Piezoelectric patch thickness (mm)	0.15
Piezoelectric patch width (mm)	20.8
End mass (gr)	45

As shown in Figure 6, a nonlinear piezoelectric energy harvester with the proposed geometrical properties is designed and simulated in the commercial software Ansys, and a base acceleration similar to Figure 3 at a speed of 4 km/h was applied to it.

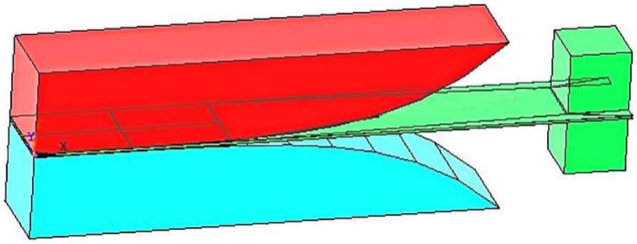

Fig.6. The proposed nonlinear energy harvester with curved supports

The proposed nonlinear energy harvester is designed for four different curved surfaces, and the best model with the most energy harvested is selected. The curved surfaces are described as $S = D(z\ /\ L_{Surf})^n$. In this equation, D, z, and L_{surf} are respectively the distance between the beam end and the support end in non-swing mode, the distance from the origin in the direction of the beam length, and the length of the curved surfaces. In this study, the energy harvester is designed for n=2, 3, 4, 5. The amount of electric power generated by the harvester obtained is shown in Figure 7. The results indicate that the nonlinear harvester with n=5 harvests more electrical power than others.

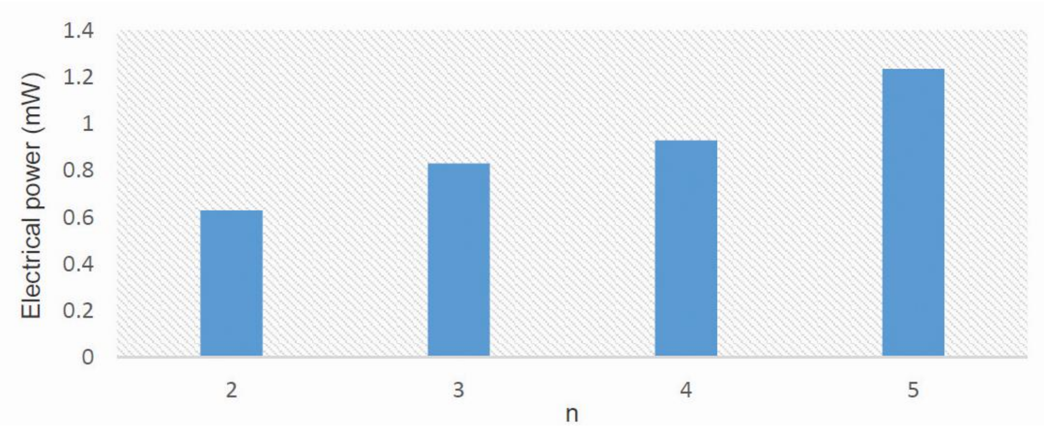

Fig.7. The nonlinear piezoelectric energy harvester (FEM results)

The nonlinear piezoelectric energy harvester with n=5 curved surfaces is optimized for electrical resistivity. Figure 8 demonstrates the nonlinear energy harvester electrical power versus the external load. According to Figure 8, the maximum power obtained at R=70 kΩ is 1.85 mW.

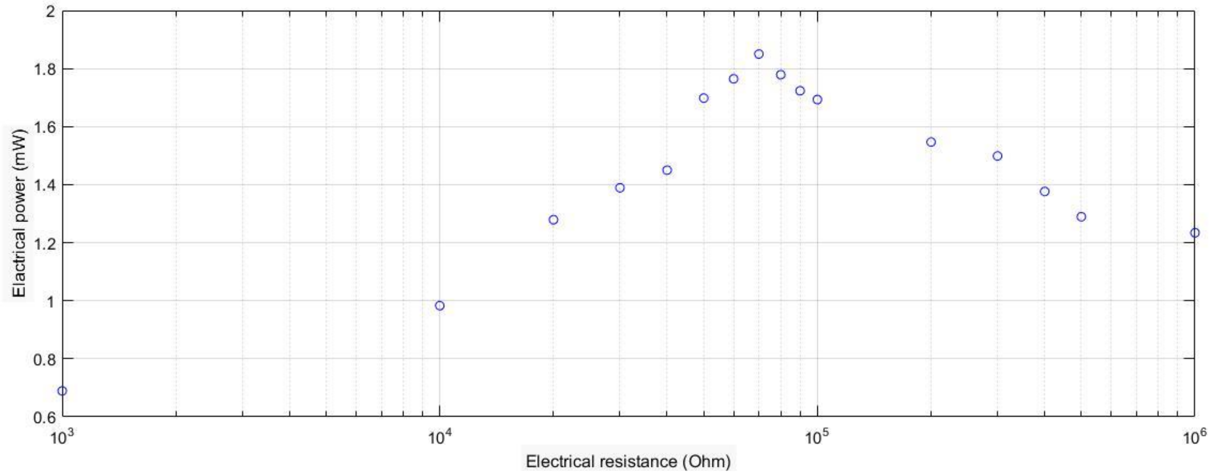

Fig. 8. Optimization of the proposed energy harvester for various electrical resistivity (FEM results)

4. Experimental setup

The nonlinear piezoelectric energy harvester, as detailed in the preceding section, was physically constructed and subjected to testing, as illustrated in Figure 9.

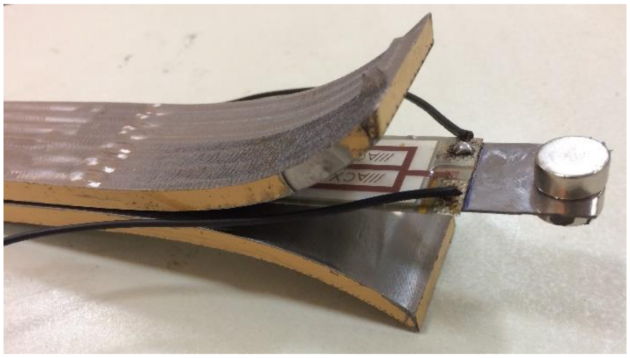

Fig. 9. Optimized nonlinear piezoelectric harvester with curved supports

As shown in Figure 10, the experimental setup consists of three main components: a treadmill, a Slam Stick vibration sensor, and the nonlinear energy harvester. The placement of the energy harvester is such that it receives the acceleration generated by the foot's motion, specifically the component perpendicular to the direction of the foot's movement during walking, serving as the base excitation for the energy harvester. The Slam Stick vibration sensor is responsible for recording the acceleration of the foot during walking. Additionally, the induced voltage generated in the piezoelectric energy harvester is measured and captured using an oscilloscope.

Fig.10. The schematic of the nonlinear energy harvester test setup

The experiments encompassed a range of seven different speeds, with data recorded for both the base acceleration and harvested electrical power at each speed. Table 3 provides a summary of the harvested power results for each test. Notably, the findings reveal a positive correlation between increasing walking speed and enhanced electrical power output from the energy harvesting system.

Table 3. The output power of the nonlinear energy harvester (experimental results)

Walking speed (km/h)	**Electrical power (mW)**
2	**0.64**
3	**1**
3.5	**1.44**
4	**1.68**
4.5	**2.56**
5	**5.76**
5.5	**7.84**

At a speed of 4 km/h, the measured electrical power harvested was recorded at 1.68 mW, while the finite element model predicted a value of 1.85 mW. This slight discrepancy represents an error of approximately 10%, a level of variance that falls within an acceptable range.

5. Conclusions

The present work examined energy harvesting using a nonlinear piezoelectric energy harvester. Initially, the performance of the nonlinear energy harvester with a linear counterpart was compared, highlighting the advantages of utilizing curved supports in the nonlinear design. This comparison underscored the effectiveness of nonlinear configurations for energy harvesting applications.

Subsequently, a nonlinear energy harvester was designed and built specifically tailored to harness energy from the foot swing motion during walking. The electrical resistance was optimized through finite element simulations, achieving a peak power output of 1.85 mW.

To validate the real-world performance of the optimized harvester, it was fabricated and rigorously tested across a range of walking speeds, totaling seven distinct conditions. The experimental results demonstrate the harvester's ability to generate electrical power under varying walking speeds. Notably, the analysis revealed a strong correlation between the finite element simulations and experimental measurements, particularly at a walking speed of 4 km/h.

These findings highlight the promise of nonlinear piezoelectric energy harvesters, particularly those incorporating curved supports, for practical energy harvesting applications. The study not only contributes to the understanding of energy harvesting from foot motion but also emphasizes the potential for real-world implementation, offering insights into the optimization, design, and correlation between simulations and experiments.

In conclusion, this study has shed light on the effectiveness of nonlinear piezoelectric energy harvesters, particularly those featuring curved supports, for practical energy harvesting applications. While the empirical findings provide valuable insights into real-world performance, future research could explore the development of comprehensive theoretical models to complement and further validate the empirical results presented here. This integration of theory and experimentation has the potential to advance the understanding and optimization of nonlinear energy harvesting systems, paving the way for broader applications in renewable energy generation.

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Conflict of interest statement

The authors declare no conflict of interest in preparing this article.

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