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AN IMPACT-BASED PIEZOELECTRIC ENERGY HARVESTER UTILIZING SPHERICAL MASS COLLISION PHENOMENON– SMART 2023

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Abstract. The base-excitation piezoelectric energy harvesters have been vastly investigated under periodic base excitation as a conventional method. However, the waveforms of environment's vibrations are mostly non-harmonic low-frequency periodic signals that reduce the efficiency of the harmonic-based resonance harvester. This study presents an alternative piezoelectric energy generation, the impact-based piezoelectric energy harvester concept rather than the typical harmonic-based one. The harvester benefits from impact excitation, leading to higher frequencies around the harvester's natural frequencies. The impact concept is utilized for energy harvesting based on contact between a piezoelectric patch and a miniatured spherical mass. An experimental study was carried out to evaluate the effects of impact velocity and boundary condition on the dynamic behavior and power generation of the piezoelectric energy harvester. Moreover, a finite element model implemented a feasible framework to investigate the output power of the energy harvester under various impact forces. The results demonstrated μJ-scale energy generation by a single impact, indicating great energy generation possibilities for ultra-low-frequencies. The results also indicated that the boundary condition plays a critical role in energy harvesting, affecting the probability of voltage cancelation phenomenon occurrence. It was shown that the optimal boundary condition decreases the negative effects of voltage cancelation to improve the performance of the impact-based energy harvester.

Keywords: Energy harvesting, piezoelectric patch, impact force, finite element method, spherical mass.

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1 INTRODUCTION

Advancements in electronic technology have reduced energy consumption for electronic devices, allowing energy harvesting methods from environmental sources to supply low-powered devices in remote and inaccessible areas, rather than relying on traditional batteries [1]. Mechanical vibration has emerged as a promising and sustainable energy source among possible energy harvesting sources due to its widespread availability in different environments and ease of system integration [2]. As a result, a range of mechanical vibration-based approaches has been proposed, electromagnetics [3], triboelectric [4], and piezoelectric[5], to name a few. The piezoelectric method has become increasingly popular because of its stable performance and small dimension, which makes it well-suited for embedding into low-powered devices.

Despite the advantages of piezoelectric energy harvesters (PEHs), certain limitations restrict their application. For instance, the narrow frequency band of PEHs complicates frequency matching between environment vibration and the harvester's natural frequency. There are several techniques, such as adding tip mass, that can mitigate this issue to some extent [6], but achieving frequency matching for low-frequency environmental vibrations (e.g., 1~2 Hz), remains a significant challenge. Therefore, the performance of PEHs under low-frequency vibrations is reduced remarkably.

Frequency-up conversion mechanisms play a vital role in boosting the efficiency of piezoelectric energy harvesting systems by facilitating the conversion of low-frequency vibrations into higher-frequency excitation. Several techniques have been proposed and investigated in the field of piezoelectric energy harvesting to achieve frequency-up conversion. For instance, the utilization of nonlinear effects in PEHs can lead to the generation of higher-frequency electrical outputs, such as internal resonance [7], [8], snap-through buckling [9], [10], and mechanical impact [11], [12] phenomenons.

The mechanical impact mechanism in literature has been considered the most conventional approach for achieving the frequency-up conversion effect [13]. There is a lack of research on the study of PEHs when subjected to impact excitation using a spherical solid mass under various conditions. This paper studies a PEH placed on a clamp under the impact force of a spherical solid mass to address this issue and bridge the gap in current knowledge. Indeed, the impact phenomenon converts low-frequency inertia excitation to a wide range of higher frequencies [11]. So, the impact phenomenon can significantly increase the excitation frequency level leading to improvement in energy harvesting performance.

This paper is organized as follows. Section 2 presents the design configuration of the proposed mechanism. Section 3 conducts a finite element model by COMSOL Multiphysics to predict the power output. The constructed experimental setup is described in Section 4. In section 5, the finite element model is validated by experimental results, and a parametric study is performed to examine the effects of different parameters on energy harvesting performance. Section 6 summarizes this study's achievements and presents some suggestions for further investigations on future works.

2 DESIGN CONFIGURATION

The principle configuration of the impact-based mechanism is shown in Fig. 1. The piezoelectric patch consists of a middle substrate layer (brass) and two active piezoelectric layers (PZT-5A), which are well bonded together. This piezoelectric patch is mounted on a clamp clip, which is constrained by the clamp's two legs. The centerlines of the MPB and clamp are coincided and positioned in a specific plane to ensure precise alignment. In addition, a spherical steal mass with a diameter of 3.18mm and weight of 0.13gr is released at specific heights on top of the patch with a zero initial velocity. The mass is speeded up by the gravitational force toward the piezoelectric patch. The mass collides with the piezoelectric patch on its centerline, which applies an impact force to the piezoelectric patch. Therefore, the piezoelectric patch converts high-frequency mechanical vibration to electrical output.

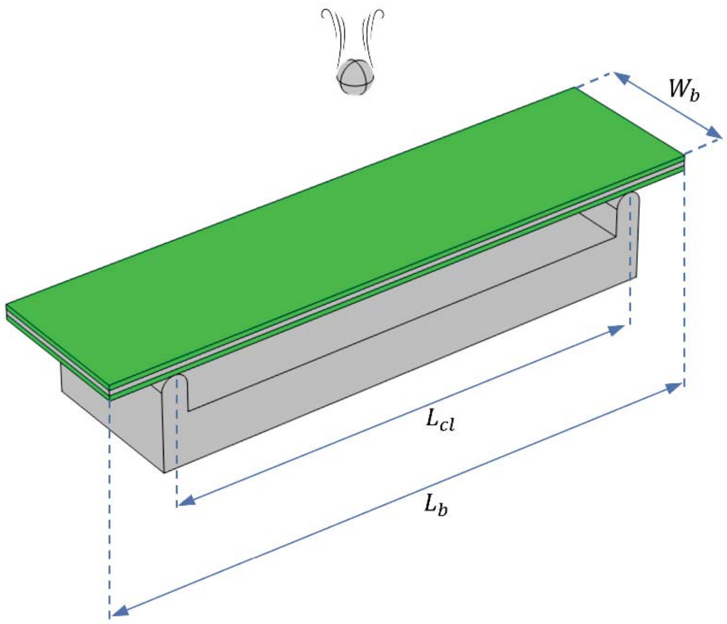

Figure 1: The configuration of the impact-based mechanism.

The poling directions of the upper and bottom piezoelectric layers are shown in the cross-section view in Figure 2. Although these poling directions are identical, the electric field directions created by pure bending vibration are opposite on these layers due to opposite bending stress/strain. Therefore, the electrical connection should be parallel, as shown in Figure 2.

Figure 2: The poling direction of upper and bottom piezoelectric layers.

3 FEM MODELING

The proposed impact-based PEH is modeled by the finite element method (FEM) in COMSOL Multiphysics to predict the harvester's output in different conditions. This model includes solid mechanics, electrostatic, and electrical circuit modules. The primary focus of this study is on the impact analysis of the PEH. To this end, a contact node is included in the solid mechanics module to assign relevant properties and settings for impact analysis. The piezoelectric model in connection with a resistive load of R is illustrated in Figure 3-a. Contact analysis generally needs nonlinear solvers, which increases the computational load. A model simplification is proposed to facilitate the computing model with lower computational resources and time. The impact-based energy harvester has two symmetry planes zx and yz, due to symmetrical boundary conditions and central-point load from the spherical ball. Therefore, the original model in Figure 3-a can be separated into four symmetrical sub-models, as shown in Figure 3-b. The final simplified model is a quarter of the original model, shown in Figure 3-c. It is noteworthy that applying appropriate symmetrical electrical conditions is essential. In this regard, the simplified model is connected with resistance equivalent to 4R rather than resistance R. As mentioned before, the origin of the coordinate system XYZ is positioned at the piezoelectric patch's center point. It is worth noting that the z=0 position coincides with the neutral surface of the piezoelectric patch.

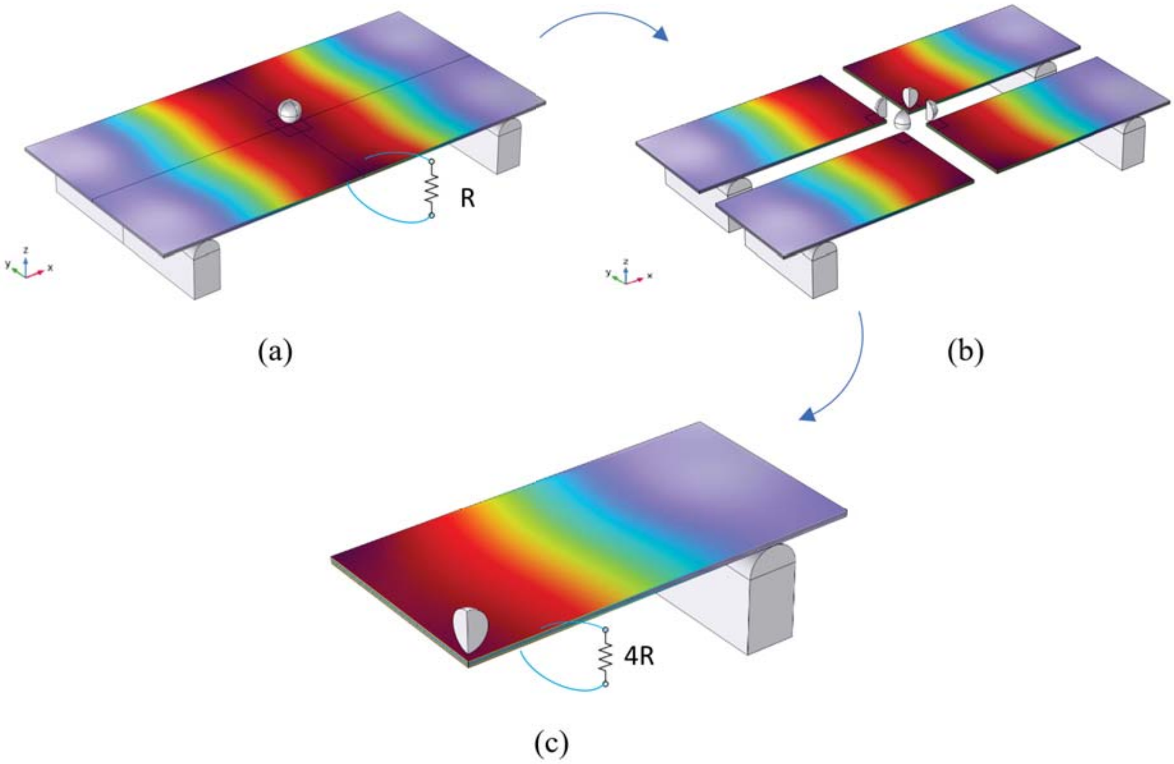

Figure 3: Simplification of the proposed model by symmetry planes, (a) main model without simplification connected with resistance R, (b) four separated models by symmetry planes zx and yz, (c) final simplified model connected with resistant 4R.

4 EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in Figure 4, which is prepared to study the proposed system and validate the FEM model. This setup comprises four main parts, including the piezoelectric patch, spherical mass, bottom clamp, and ball height adjuster. In this paper, the piezoelectric patch (with length L_b=63.5mm, width W_b=31.8mm, (each) piezoelectric thickness t_p= 0.19mm and substrate thickness t_s= 0.13mm) is connected to the resistance R=2340Ω, according to Figure 2. The bottom clamp (PLA) with variable length L_{cl} holds and constrains the piezoelectric patch. The ball height adjuster with nine-stage height levels controls the impact force level and facilitates aligning the exact initial position of the ball. Lastly, the output of the energy harvester is recorded by a data acquisition (NI cDAQ-9172, NI 9229).

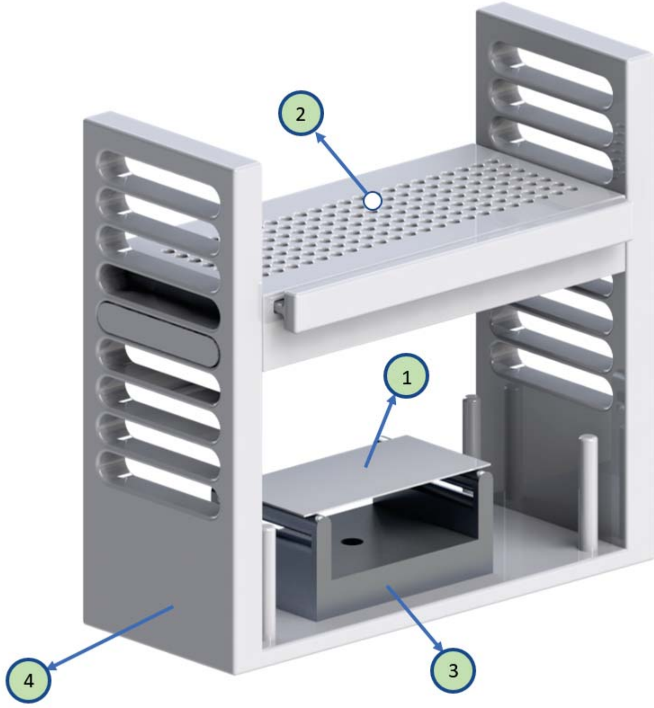

Figure 4: The schematic of the experimental setup consists of the (1) piezoelectric patch, (2) spherical ball, (3) bottom clamp, and (4) ball height adjuster.

5 RESULTS AND DISCUSSION

This section studies and discusses the proposed impact-based energy harvester's outputs. Accordingly, several experimental tests are accomplished under different conditions. In addition, the prepared FEM model is validated against these experimental results.

5.1 EXPERIMENTAL RESULTS AND FEM MODEL VALIDATION

The spherical ball is released from the initial height of H_1, applying the impact force to the piezoelectric patch's center point. This experimental test measures the generated voltage when the energy harvester is connected to the resistance of R=2340 Ω. Several tests with various H_1 and L_{cl} parameters are carried out to evaluate the effects of these parameters on energy harvesting performance. The derived experimental results versus different H_1 (7.7 and 11.7cm) and L_{cl} are shown in Figure 5. Similarly, the FEM model is subjected to the same experimental conditions, and its results are compared to the experimental results, as depicted in Figure 5.

This comparison indicates that the model developed in this research predicts well the energy harvester's outputs under various conditions. These comparisons show that this FEM model captures the complex mechanical interaction between the impact of two structures and its resultant Multiphysics output in piezoelectricity.
Several factors may account for the discrepancies between the experimental and FEM model results. For instance, the PEH outputs may be highly sensitive to the impact location, considering that the ball could collide with the piezoelectric patch at various points around the center point in experimental tests. Moreover, the friction in contact is not defined in the FEM model, which can affect the results positively. Notably, the evaluation of these factors is outside the scope of this study and will be addressed in future studies.

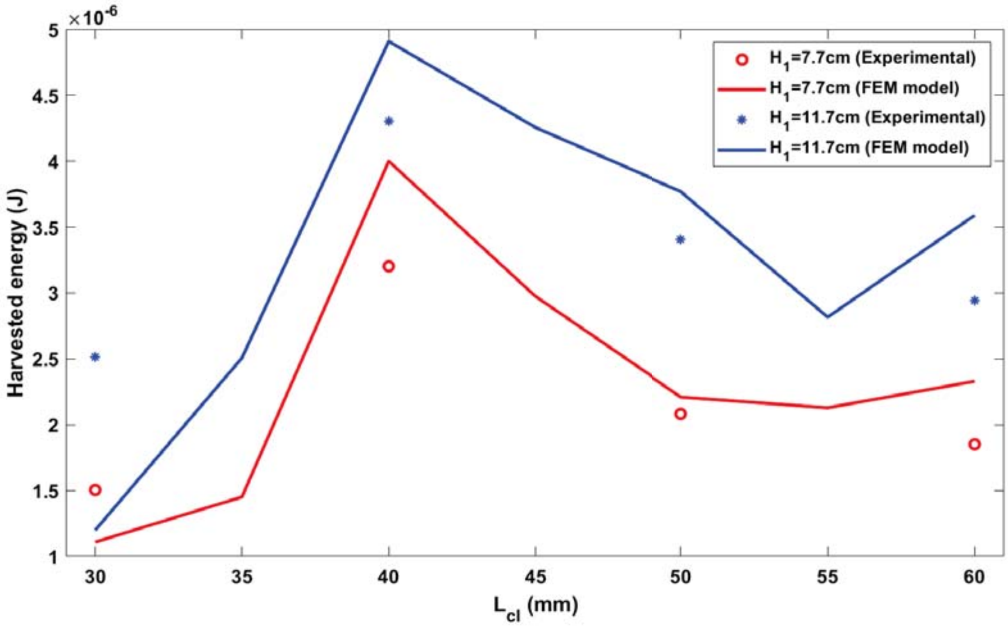

Figure 5: The harvester energy per different H_1 and L_{cl} derived by experimental results and FEM model.

As an optimization parameter, Figure 5 shows that the maximum harvested energy occurs once L_{cl} equals 40mm. In the following, the FEM model is studied to scrutinize the variation of harvested energy versus L_{cl}.

5.2 STUDY OF THE FEM MODEL

A line segment with coordinates $y=W_b/2$ and $z=h_s/2$ from $x=0$ to $x= L_b/2$, as shown in Figure 6, is defined to derive the variation of longitudinal strain, S_x, along this line.

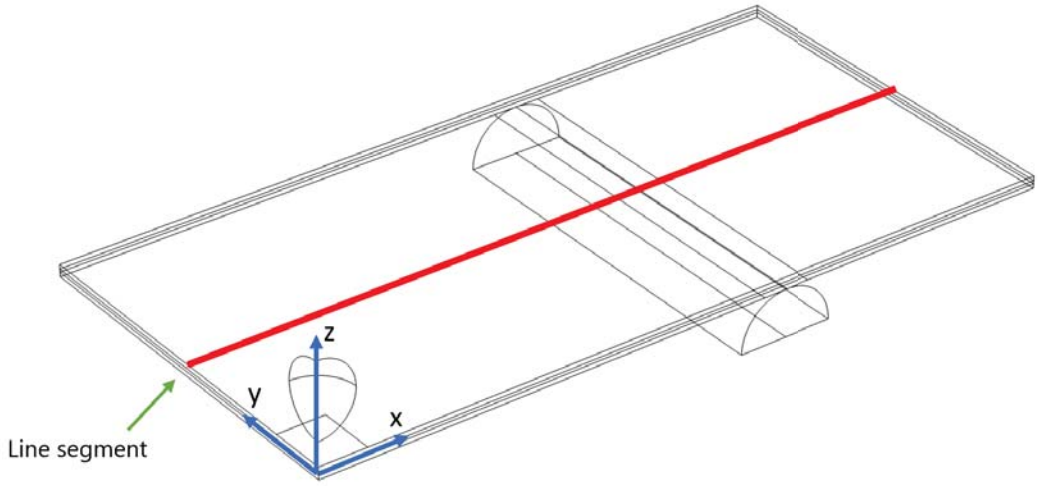

Figure 6: The defined line segment with coordinates x=[0 $L_b/2$], y=$W_b/2$, and z=$h_s/2$.

Figure 7 depicts the longitudinal strain over time across the defined line segment for the boundary condition of L_{cl}=30mm with an initial height of H_1=117mm. Consistency in the direction of the strain/electric field along the piezoelectric patch's length is crucial. The uniform signs of the strain and electrical field enhance energy harvesting performance, while different signs significantly decrease the energy harvester performance due to the voltage cancelation phenomenon [15]. Figure 7 illustrates that the longitudinal strain across the defined line segment at specific times is not uniform, and its direction changes around so-called strain nodes. The longitudinal strains at shown times have mostly two strain nodes, which are prone to voltage cancelation.

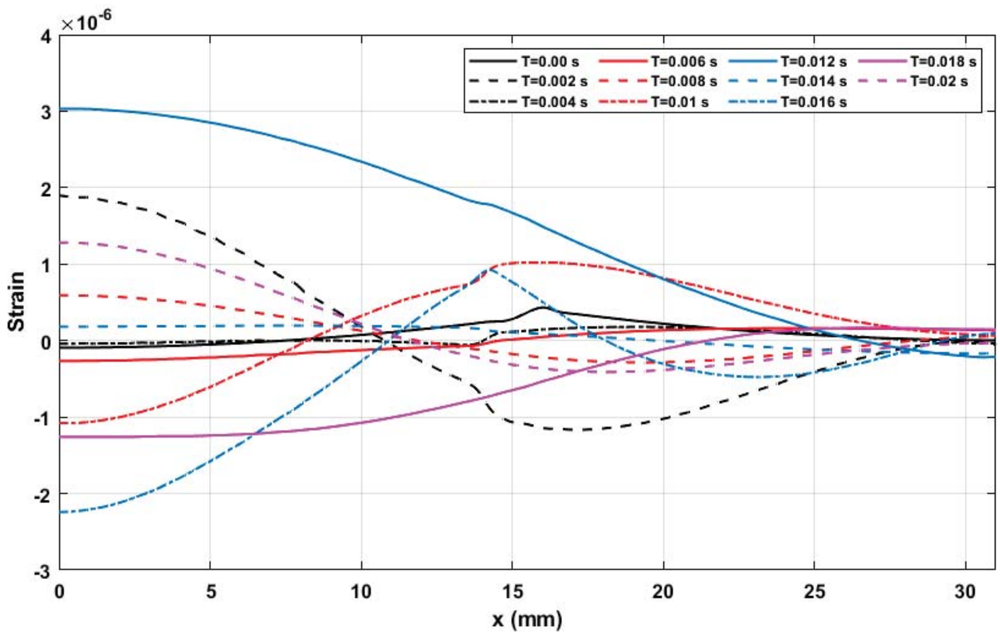

Figure 7: The variation of longitudinal strain across the defined line segment (L_{cl}=30mm).

Similarly, Figure 8 illustrates the same longitudinal strain variation but under the boundary condition of L_{cl}=40mm. Most of the shown longitudinal strains have one strain node around x=25mm. Indeed, these strain nodes' location is near the end of the piezoelectric patch (x=25mm), which enhances the sign uniformity of the strain and electrical field on the piezoelectric patch. As a result, the boundary condition of L_{cl}=40mm is unaffected mainly by lower cancelation voltage deficiency than the previous boundary condition (L_{cl}=30mm).

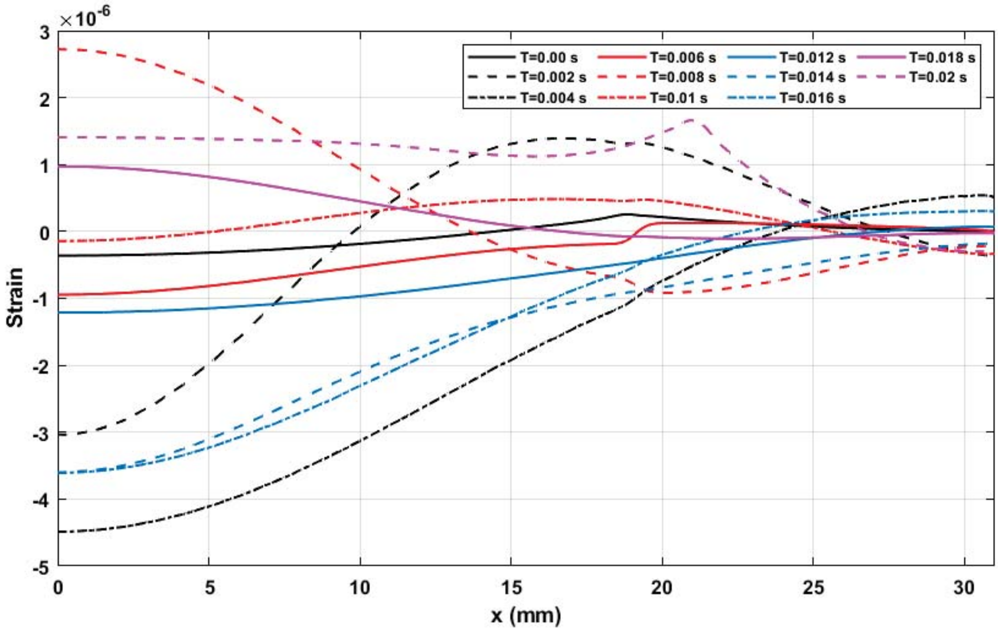

Figure 8: The variation of longitudinal strain across the defined line segment (L_{cl}=40mm).

As a comprehensive criterion, the integration of longitudinal strain (ILS) over length at different times is presented as follows

$$ILS(t) = \left| \int_0^{L_b/2} S_x(x,t)\,dx \right| \tag{1}$$

The ILS of the longitudinal strains shown in Figure 7 and Figure 8 are illustrated in Figure 9 at different times. Additionally, the average of ILS is shown in Figure 9. The ILS average of the boundary condition L_{cl}=40mm (3.09×10^{-8}) is higher than that of the boundary condition L_{cl}=30mm (1.76×10^{-8}), which is consistent with better performance in the former boundary condition (L_{cl}=40mm).

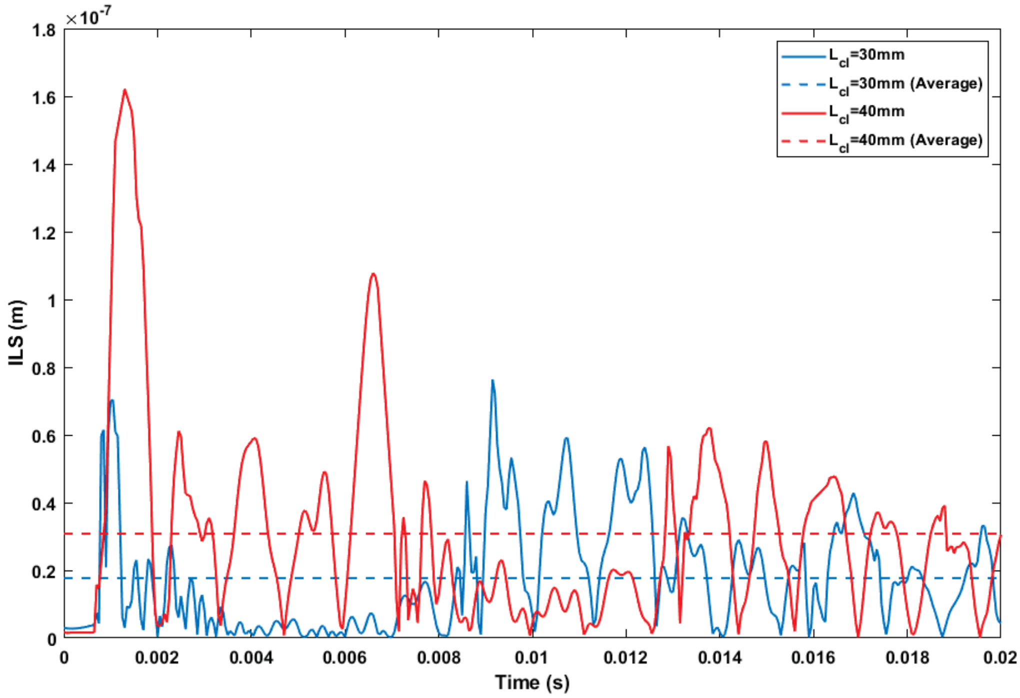

Figure 9: Integration of longitudinal strain over length at different times.

6 CONCLUSION AND FUTURE WORKS

This research investigated an impact-based PEH subjected to impact force applied by a spherical ball. An experimental setup was constructed to measure the output of the PEH under different initial heights and boundary conditions. Similarly, a FEM model was developed by COMSOL Multiphysics to predict the outputs of the PEH. The FEM model was validated against the experimental results. The results showed that different boundary conditions affect the dynamic response of the piezoelectric patch. As a result, some boundary conditions increase the number of strain nodes, which increases the adverse effects of voltage cancelation. Therefore, it is crucial to consider the side effects of the voltage cancelation phenomenon in impact-based PEHdesign to prohibit this phenomenon.

Following future work is considered for further studying of this topic: (1) the study of different impact positions and angles rather than the vertical impact on the center point, (2) evaluation of the spherical ball's material properties (e.g., Young's modulus) and its effect on contact force and frequency excitation. These studies can enhance energy harvesting performance remarkably for powering electrical components in different applications such as structural health monitoring. In addition, these findings can be utilized to design impact-based energy harvesters for specific applications with low-frequency excitation, such as powering implantable cardiac pacemaker devices.

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