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***Research paper***

# The Effect of Axial Displacement of Magnets in Piezoelectric Energy Harvester

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**Abstract**

The utilization of vibration energy harvesters as a substitute to batteries in wireless sensors has shown prominent interest in the literature. Various approaches have been adapted in the energy harvesters to competently harvest vibrational energy over a wider spectrum of frequencies with optimize power output. A typical bistable piezoelectric energy harvester, where the influence of magnetic field is induced into a linear piezoelectric cantilever, is designed and analyzed in this paper. The exploitations of the magnetic force specifically creates nonlinear response and bistability in the energy harvester that extends the operational frequency spectrum for optimize performance. Further analysis on the effects of axial spacing displacement between two repulsive magnets of the harvester, in terms of x-axis (horizontal) and z-axis (vertical) on its natural resonant frequency and performance based on the frequency response curve are investigated for realizing optimal power output. Experimental results show that by selecting the optimal axial spacing displacement, the vibration energy harvester can be designed to produce maximized output power in an improved broadband of frequency spectrum.

***Keywords***: *Energy Harvesting; Nonlinear Dynamics; Vibration; Piezoelectric; Repulsive Magnetic Force*

## 1. Introduction

Vibrational energy harvesting through translation of ambient mechanical vibration energy to usable electrical energy has established emergent attention over the years. Noteworthy progress and further understanding of the underlying mechanism behind vibration energy harvesting has been well established by researchers to enhance the power output of the energy harvesters. These energy harvesters principally rely upon the physics of either electromagnetic [1], electrostatic [2], magnetostrictive [3], or piezoelectric [4] energy conversion mechanism. These harvested energy by using the piezoelectric effect has received promising outcomes in powering micro electromechanical systems and replacing small batteries that have a restricted life duration.

A conventional piezoelectric energy harvester (PEH) is usually designed using a single piezoelectric cantilever with or without load as a linear resonator, and typically suffers from a narrow operating frequency bandwidth [5]. The field of vibration energy harvesting has now progressed from linear single resonant frequency harvester to more complex multi-frequency energy harvester for better power output with minimal ambient vibration energy. Further research has resulted in the development of several structural designs such as increasing the numbers of cantilevers [6], introducing attractive and repulsive magnetic effect [7] and frequency self-tuning [8] with the aim to increase the operating frequency bandwidth. Most designs have seen practical success depending on its viability and applications.

Bistable configurations characteristically consists of the usage of magnetic force to create two stable equilibria energy have also been studied enthusiastically by many researchers [9-11]. Many researchers applied the extension of magnetic restoring force rule [12] to design the piezoelectric energy harvester and creates the possibility of introducing nonlinearity which leads to widening of the operating frequency bandwidth. The manifestation of magnetic nonlinearities in the energy harvester primarily results in changing the softening and hardening behaviour of the piezoelectric cantilever. However, most research studies concentrate only on one direction of spacing distance where the natural resonant frequency of the energy harvester and thus its performance may not significantly affected [13, 14].

In this study, the significance of axial spacing displacement in terms of x-axis (horizontal) and z-axis (vertical) between two repulsive magnets on the resonant frequency and harvester's performance will be discussed. This model takes into consideration the effects of introducing magnetic force into a single unimorph cantilever beam with magnet as the load. This article presents an empirical study on the usage of magnetic force and its spacing displacement variations to increase the spectrum of frequency for broadband energy harvesting purposes.

This paper is organized as follows. In section 2, the related methodology and conceptual of the magnetic force effect on the piezoelectric cantilever is described. The influence of the axial spacing displacement between two magnets in terms of x-axis and z-axis on its resonant frequency is also presented in section 3. In section 4, the analysis on the impact of axial spacing displacement between two magnets on its performance of the harvester is investigated. Finally, the research study of this paper is summarized and concluded in the last section.

## 2. Methodology and Design Analysis

The bistable piezoelectric energy harvester is designed by introducing two magnets into a linear piezoelectric cantilever beam setup. It is comprises of an unimorph piezoelectric cantilever beam which is firmly clamped at one end and held to reduce the effect of gravity. A magnetic mass weighing 0.75 gram is attached at the piezoelectric cantilever free end to act as a mass as well as to provide the restoring magnetic force for the energy harvester. Another similar magnetic mass is fixed in a static position and is oriented in opposite polarity with the magnetic mass on the cantilever end. This static magnet will be adjusted accordingly during the experiment in terms of displacement distance in x-axis,   and displacement distance in z-axis,   as shown in Fig. 1.

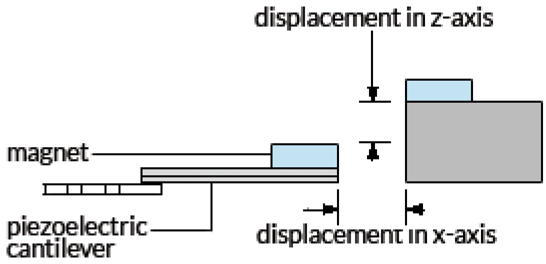


**Figure 1:** A schematic diagram of piezoelectric energy harvester in axial displacement for x-axis and z-axis.

The spacing displacement in y-axis will be kept constant throughout the experiment. The magnets are placed in such a manner that it provides a repulsive force between each other as the spacing distance between the magnets decreases. The piezoelectric energy harvester under analysis is subjected to a transverse harmonic displacement by the seismic vibration shaker. It is placed under the vibration source with constant acceleration level of 1-G level as the frequencies of the vibration shaker is varied accordingly. The apparatus for the experimental setup is as depicted in Fig. 2.

This design is used to adjust the stiffness of the piezoelectric cantilever by varying the distance between the magnetic mass horizontally and vertically. The magnets are placed in repulsive configurations where a decrease in the displacement between both magnets will cause a change in the static position of the piezoelectric cantilever. The change of static position is dependent on the amount of hardening effect as the spacing displacement between the two repulsive magnets decreases.

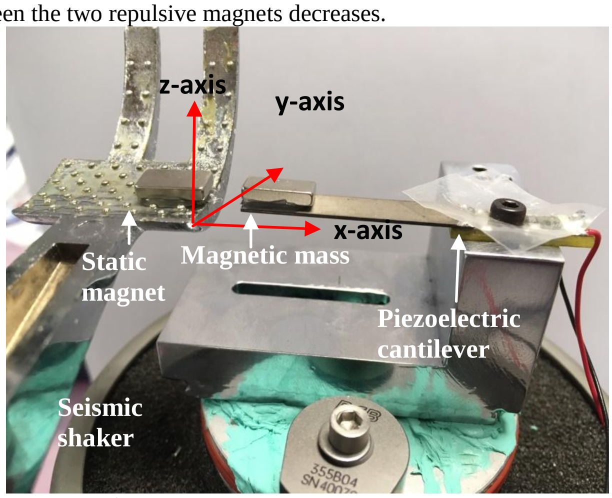


**Figure 2:** Layout of experiment apparatus and its respective axial displacement labelled accordingly.

The empirical study in this paper is distributed into two categories. The first part of the experiment involves studying the variations of the resonant frequency of the energy harvester as the magnetic spacing displacement changes vertically in z-axis ( ) between two magnets in repulsive mode. Fig. 3 shows an example of the experimental setup after changing the axial displacement between two repulsive magnets in z-axis. The same experiment will then be repeated for different axial displacement of the magnets in x-axis, ( ) to analyse the differences in resonance frequency as the restoring magnetic force between the magnets changes. By analyzing the effects on magnetic force on the resonant frequency of harvester, further investigations can be done to design a robust nonlinear broadband energy harvester.

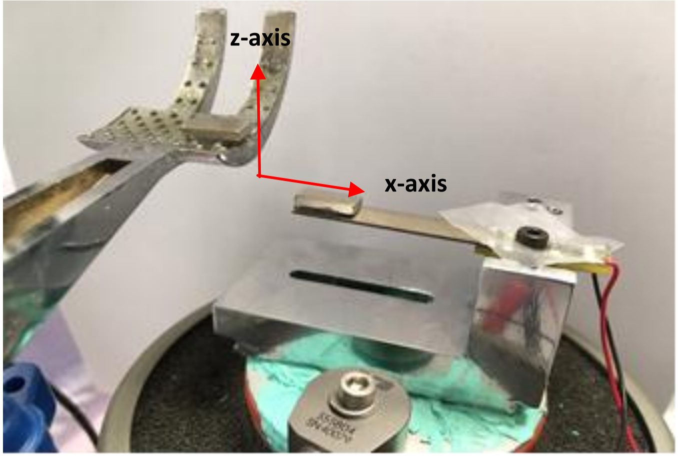


**Figure 3:** Layout of experiment apparatus after changing the axial displacement with respect to z-axis.

In the second part of the experiment, the performance of energy harvester will then be analyzed further based on the differences of the spacing displacements. The performance of the harvester will be evaluated based on the open circuit voltage generated by the piezoelectric cantilever for a diverse variations of spacing displacement between the magnets in x-axis and z-axis respectively.

Observe that as the axial displacements between the magnets changes in both x-axis and z-axis, the actual spacing displacement between the two repulsive magnets is actually a diagonal distance between the magnets and can be written as

Axial Spacing Displacement, $r_{xy} = \sqrt{D_x^2 + D_Y^2}$

## 3. Results and Discussion

### 3.1 Analysis on the Effect of Axial Displacement between Magnets on the Resonant Frequency of Piezoelectric Cantilever

The effect of repulsive magnetic forces between two magnets of the energy harvester in adjusting the cantilever resonance frequency has been investigated and analyzed as follows. Firstly, the displacement between the two repulsive magnets are adjusted along the x-axis, ensuring there is no changes in the y-axis and z-axis of the cantilever beam. The axial displacement is then varied accordingly along the z-axis to observe the changes in resonant frequency of the cantilever. The plotted curves in Fig. 4 shows the deviations of the resonant frequency as a function of z-axis spacing displacements between two repulsive magnets for three different spacing displacements in x-axis.

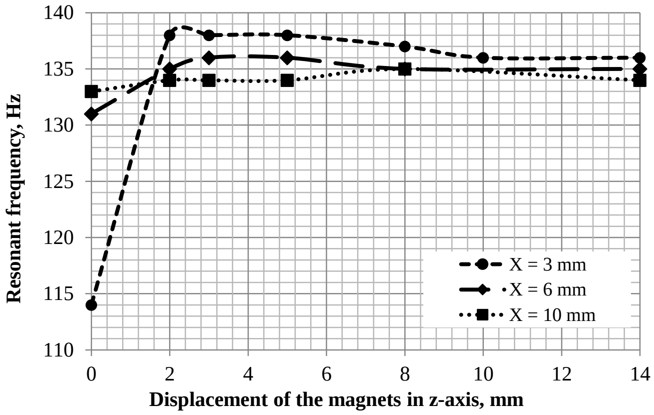


**Figure 4:** Deviations of the resonant frequency of the energy harvester as a function of z- axis displacement for x= 3 mm, 6 mm and 10 mm displacment in the x-axis.

Based on the analysis, it is observed that the repulsive magnetic force is most prominent for x-axis spacing displacement of x equals to 3 mm where the resonant frequency changes abruptly as the displacement in z-axis varied accordingly. Observe that when the cantilever is placed on the same level as the static magnet where z = 0 mm, the resonant frequency of the energy harvester is at its minimum level of 114 Hz. As the z-axis displacement increases, the resonant frequency increases drastically and fluctuates between 136 Hz to 139 Hz. As the restoring magnetic force is still quite strong at this spacing distance, a slight change in the spacing displacement in z-axis will cause a significant effect on the variations of resonant frequency. The static position and bending effect of the piezoelectric cantilever beam tend to change respectively when the strength of the repulsive magnet force increases, and thus, consequently causing a drastic change of resonant frequency response. This illustrates that the repulsive magnetic force can be applied to tune the resonant frequency of the energy harvest by changing the axial displacement between the magnets.

As the spacing displacement in x-axis increases to 6 mm and 10 mm as illustrated in Fig. 4, the resonant frequency of the energy harvester shows less significant fluctuations when the static magnet is shifted vertically along the z-axis. The resultant resonant frequency of the energy harvester seems to stabilize, signifying the vanishing effect of the magnetic force especially the spacing displacements between the two magnets increases to above 10 mm in z-axis.

As the consequence of this analysis, it is observed that the repulsive effect between the magnets are stable only at x-axis spacing distances above 6 mm in the energy harvester. For smaller values of the x-axis spacing distance, the hardening effect of the both magnets increases relatively causing the instability in the resonant frequency of the energy harvester. It is also noted that the resonant frequency of the energy harvester is less likely to be affected by the variations of spacing distance in z-axis when the x-axis spacing displacement is above 6 mm. This results is very valuable to design the resonant frequency of the energy harvester for matching of accessible excitation frequency in the surroundings.

## 3.2 Analysis on the Effect of Axial Displacement between Magnets on the Performance of the Energy Harvester

In this section, the analysis on the performance of the energy harvester as the distance between the magnets changes vertically and horizontally is studied. The frequency response curves of the open circuit root mean square (rms) voltage for different ranges of spacing distances between the two repulsive magnets are plotted accordingly.

Fig. 5 shows that the frequency response curves of the energy harvester when the magnets are placed in a horizontal separation of 3 mm. The plots show that the resonant frequency and voltage output of the harvester changes drastically with minimal deviations of vertical spacing displacement between magnets in z-axis. Observe that when both the repulsive magnets are in parallel and equal height with each other (z = 0 mm), the level of harvested voltage at resonance is almost similar with the case where the magnetic displacement is above 8 mm. However, these results may be more of interest if we intend to design a broadband energy harvester for low frequency vibrations. It is also noted that by varying the spacing distance, the energy harvester has the ability to harvest energy in a broader spectrum of frequency. For example, if the choice of harvesting energy is at the Vrms of 4V, the better choice of z-axis spacing distance would be when the magnets are of equal height with each other (z = 0 mm) where the energy harvester is able to harvest energy at the broadest spectrum of frequency compared to other z- axis spacing displacement. On the other hand, if we wish to harvest the power output at a higher Vrms of 8V, the better choice of spacing displacement between the repulsive magnets would be 3 mm in z-axis. The graphs also illustrates that the highest power output can be obtained when the magnetic force vertical spacing displacement is between 2 mm to 5 mm in z-axis. Among the 3 frequency response curves mentioned above, the best spacing distance that is able to harvest optimized energy in the broadest frequency spectrum is when the z-axis spacing displacement is 5 mm.

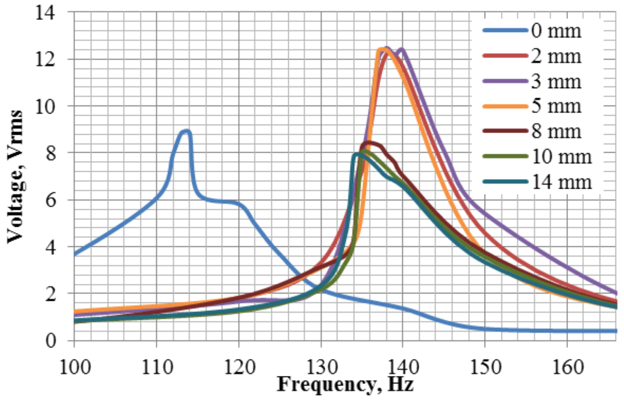


**Figure 5:** Frequency response curves of the open circuit voltage of the energy harvester for different values of z-axis displacement at horizontal displacement of x = 3 mm.

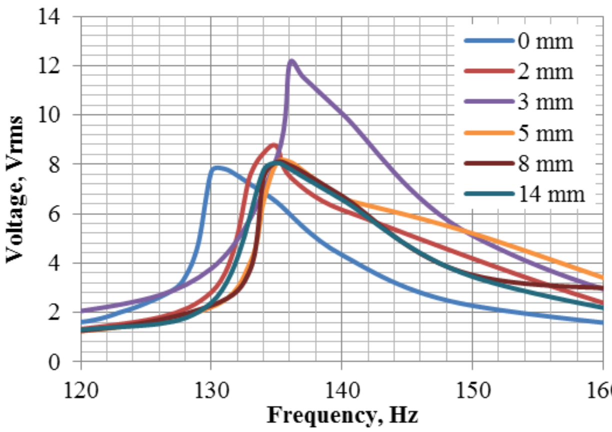


**Figure 6:** Frequency response curves of the open circuit voltage of the energy harvester for different values of z-axis displacement at horizontal displacement of x = 6 mm.

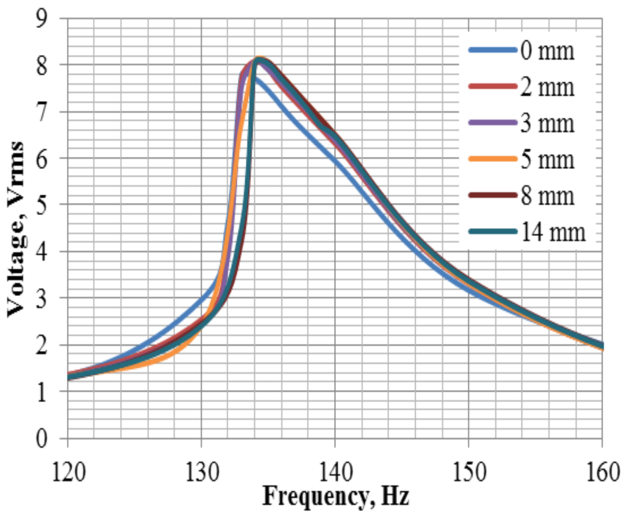


**Figure 7:** Frequency response curves of the open circuit voltage of the energy harvester for different values of z-axis displacement at horizontal displacement of x = 10 mm.

If the x-axis spacing displacement between the magnets is increase further, the resonant frequency of the energy harvester seems to stabilize and fluctuates within 130 Hz to 136 Hz for the variations of z-axis spacing displacements, as illustrated in Fig. 6. Observe that the frequency response curves also shares similar shapes as the spacing displacements between magnets varies accordingly. The plots also shows that by shifting the static magnet along the z-axis and above its original position (z = 0 mm), the energy harvester displays a better frequency response curve and provides higher level of harvested energy. Furthermore, the frequency response curves also shows that at specific z-axis spacing displacement, the energy harvester will be able to harvest energy at a broader spectrum of frequency. In this scenario, if the choice of harvesting energy is at the Vrms of 4V, the better choice of z-axis spacing distance would be when the magnets are placed at z = 3 mm between each other where the energy harvester is able to harvest energy at the broadest spectrum of frequency compared to other z- axis spacing displacement. In addition to that, for the same z-axis spacing displacement of 3 mm, the frequency response curve at x = 6 mm (Fig. 6) outperforms the energy harvester at x = 3 mm (Fig. 5) in terms of the range of frequency spectrum for broadband energy harvesting. Besides that, the voltage output of the energy harvester is at its peak when it has the axial spacing displacement of x = 6 mm and z = 3 mm at the x-axis and z-axis respectively.

Comparing Fig. 5 and Fig. 6, it is observed that when the magnets are aligned in parallel and equal height with each other (z = 0 mm), the variations of x-axis spacing displacement will cause a drastic change of resonance frequency in the energy harvester and its range of frequency spectrum. This result simply shows that the increase of hardening effect between the two repulsive magnets will cause the reduction in the width of frequency spectrum as well as changes to its resonance frequency. Since the change of spacing displacement vertically in z-axis does not affect the resonant frequency drastically, this may be a better technique to increase the spectrum of frequency for broadband energy harvesting compared to changing the spacing displacement horizontally in x-axis.

Fig. 7 demonstrates that as the spacing displacement between the two repulsive magnets goes beyond 10 mm, the effect of restoring magnetic force decreases and vanishes gradually as the axial displacements increases. Thus, frequency response curves show similar pattern of energy harvesting for all the different values of spacing displacements in z-axis. Additionally, the overall open circuit voltage and also its power output shows a decrement pattern due to the loss of restoring magnetic force in the energy harvester. However, based on the analysis of the graphs, shifting static magnet to have the vertical spacing displacement to a minimal of 3 mm along z-axis actually provides better frequency response curves with broader spectrum of frequency.
The results implies that by choosing the best optimal axial spacing displacement in terms of x-axis and z-axis displacements between two repulsive magnets, a robust and competent energy harvester can be designed to harvest energy at a broadband of frequency spectrum.

## 4. Conclusion

In this paper, the effect of axial spacing displacement between two repulsive magnets in a piezoelectric energy harvester has been studied. It is also demonstrated that the fundamental resonant frequency of the energy harvester is significantly affected by the change of x-axis spacing displacement between the magnets, but the resonant frequency may not be affected when there is variations in the z-axis spacing displacement. Furthermore, a broader spectrum of frequency for energy harvesting can be obtained through alterations of spacing displacement vertically between magnets in z-axis.

The experiment results show that by choosing the optimal axial spacing displacement between two repulsive magnets, the piezoelectric energy harvester can be designed to achieve broadband energy harvesting or to tune the resonant frequency for matching of ambient excitation frequency in the surroundings.

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