

Parameter Optimization of Nonlinear Piezoelectric Energy Harvesting System for IoT Applications

Li Wah Thong¹

Faculty of Engineering and Technology
Multimedia University, Melaka, Malaysia

Swee Leong Kok², Roszaidi Ramlan³

Faculty of Electronics and Computer Engineering
Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

Abstract—The vibrational energy harvesting has been essentially applied to power up low-power electronics, microsystems, and wireless sensors especially in the areas of Internet of Things (IoT) devices. This paper investigates the prospect of incorporating nonlinearity in a unimorph piezoelectric cantilever beam with a tip magnet placed under a harmonic base excitation in IoT enabled environment. An empirical and theoretical analysis on the impact of various parameters such as spacing distance between magnets, presence of magnetic tip mass and positioning of vibrational source on the frequency response output was performed. It was observed that the largest spectrum of frequency can be produced when at the lowest resonant frequency of the cantilever. The positioning of vibrational source deeply impacts the hysteresis region and frequency range in realizing broadband energy harvesting. The inclusiveness of vibration source on both the cantilever beam as well as the external magnets impacts the energy harvester in terms of frequency range and the minimal distance for bistable condition.

Keywords—Energy harvesting; nonlinear dynamics; piezoelectric; vibration; broadband frequency

I. INTRODUCTION

The innovations in low power electronics for Internet of Things (IoT) in a variety of capacities ranging from health facilities, smart homes, and security surveillance has been extensively researched in the literatures [1, 2]. These low power sensors and devices traditionally function using batteries that have a limited lifespan. As the demand of sustainability in IoT devices increases, the need to recharge or replace these conventional batteries are essential to ensure the system is fully operational thoroughly [3]. The application of piezoelectric cantilever effect in transforming surrounding mechanical vibration energy to operational electrical energy has gained significant research interest progressively over the years. The vibrational energy harvesting has been applied widely to supply electrical energy to power up low-power electronics, microsystems, and wireless sensors [4-6]. It has also been regarded as an alternative source to chemical batteries that are relatively small and have restricted life duration. Piezoelectric energy harvesters are usually integrated in areas where the usage of batteries is unfeasible and inappropriate. The most commonly deliberated vibration-to-electrical energy conversion mechanism in the literature is modeled using either electromagnetic, electrostatic, magnetostrictive, triboelectric or piezoelectric energy mechanism [7-9].

The single cantilever piezoelectric energy harvester (PEH) that was projected irrespective of load as a linear resonator does not provide efficient operating frequency as it characteristically suffers from a constricted operating frequency range [10]. The simplicity in incorporating piezoelectric harvesters has encouraged in-depth research to increase its performance and extending its operational frequency spectrum. Since piezoelectric energy harvester is a resonant-based model, one of the requirements to obtain maximum electrical power output is to ensure that the excitation frequency of the ambient surroundings matches to the resonant frequency of the harvester [11, 12]. A minor frequency disparity or deviations from the harvester resonant frequency will significantly reduce the harvested power as the imparted stress-strain effect in the piezoelectric mechanism has been affected accordingly. Unfortunately, in real world circumstances, the frequency spectrum of the vibrational energy in ambient environment changes dynamically and can be unpredictable over time [13]. In order to mitigate this issue, evolutions in design and parameters of the piezoelectric energy harvesting system has been expanded in several aspects such as altering design configurations [14, 15], manipulating mechanical nonlinearities [16, 17], and improving electronic circuitry [18, 19] with intentions to increase the spectrum of operational frequency and thus its power output. These innovations have seen viable success in its intended purpose to provide better solutions for vibrational energy harvesters [20].

In view of the design aspects discussed in the literatures, most of the methodology focuses on either tuning the resonant frequency or broadening the operational frequency spectrum of the energy harvester [21, 22]. For techniques involving active resonant frequency tuning, the resultant development of the energy harvester may not be practicable as the tuning of the actuators actually consume more power than the device can harvest [23, 24]. In passive resonant tuning, the increase usage of sensors and actuators indirectly create an upsurge in cost and intricacy of the system [25]. Current research for increasing the bandwidth of the operating frequency has developed positive prospective in recent years in terms of extending range of frequencies to be processed [26-29]. This innovative strategy allows the energy harvester to response to several vibration frequency excitations at the same time. There is no tuning mechanism involved; however, there may be a decrease of maximum power harvested at the instance. The strategies involved in widening the operational frequency spectrum includes designing an array of piezoelectric cantilevers as generators [30], introducing mechanical stopper to limit the

This work is sponsored by the Ministry of Higher Education Malaysia under Fundamental Research Grant scheme (FRGS/1/2020/TK0/MMU/03/13)

harvester amplitude [31], and accustoming nonlinearities into the harvester system through bistable configurations [32, 33]. Many researchers have enthusiastically expanded the bistable configurations which comprises of two stable equilibria energy states created by the exploitations of magnetic field force [34, 35]. Further exploration in the effect of restoring force by magnets and its nonlinearity may create the opportunity to extend the bandwidth of operating frequency in the energy harvesting system. With these motivations, the empirical study in this research paper thus focuses on widening the operational frequency spectrum through exploitations of magnetic field. In the literatures, most researchers study the impact of permanent magnets when only the piezoelectric cantilever was placed under seismic vibration while the external magnets were assumed to be static [36-39]. Some researchers also studied the impact of permanent magnets when both the piezoelectric cantilever beam and external magnet are placed under the same vibration. As the beam and its external magnet of the piezoelectric energy harvester are usually designed inclusively and placed together on the same vibrating platform, both the beam and external magnets will experience the same vibration and will counteract during vibration. Thus, the need to analyse and model a nonlinear energy harvesting system based on the positioning of vibration source is essential for further improvement of broadband energy harvesting.

In this paper, the noteworthy impact in terms of resonant frequency and the voltage output of the piezoelectric energy harvesting system as the relative distance between two fixed magnets in repulsion mode varies horizontally was investigated. The proposed model is designed by incorporating magnets as mass on the single unimorph piezoelectric cantilever beam and inducing the effects of magnetic field force to control the stress-strain effect in the cantilever beam. This paper discusses an experimental analysis on the effect of using magnets and its variations in spacing range towards the bandwidth of frequency spectrum for a wideband bistable energy harvesting system. Furthermore, the influence of positioning the vibration source on either the cantilever beam or both the beam and external magnets are compared to analyse its effect on the resonance frequency and voltage output of the energy harvester. A comparison in term of resonance frequency, output voltage and its spectrum of frequency between both scenarios will be done accordingly.

This paper is organized as follows. Firstly, the research methodology and its concept in using the magnets as load for the piezoelectric cantilever are described in Section 2. Furthermore, Section 3 presents the consequence of extending the horizontal displacement between the two magnets on the piezoelectric resonant frequency. In Section 4, further investigation is done to observe the consequential outcome of spacing distance between magnets on the performance of the harvester. Lastly, a summary of the overall research results in the paper is established and elaborated in the final section.

II. THEORETICAL ANALYSIS

A. Modeling and Design Analysis

The design of the bistable piezoelectric energy harvesting system involves a unimorph piezoelectric cantilever beam and two magnets that will be applied as mass and also for its

repulsive-attractive mechanism. The piezoelectric cantilever is setup by clamping one of its end firmly onto the vibration shaker with the aim to decrease the effect of gravity. At the other free end of the cantilever beam, a magnetic mass that weighs approximately 0.75 gram will be fixed to the piezoelectric cantilever to behave as a mass as well as to be responsible for providing the magnetic force restoration for the system. Subsequently, an additional alike magnetic mass is secured in a fixed location but is positioned in reverse polarity compared with the magnetic mass on the cantilever free end. During the experiment, the magnet in the fixed position will be displaced along the x -axis accordingly to provide displacement, d . The setup of these magnets will provide a variation of repulsive magnetic force strength as the distance between both magnets adjusted accordingly. The controllable vibration shaker functions to provide a transverse harmonic displacement for the piezoelectric cantilever throughout the experiment. In this paper, a comparison will be done to observe the impact of the magnets on the resonance frequency and voltage output when the vibration source is placed differently as illustrated in Fig. 1. In Fig. 1(a), the piezoelectric cantilever beam is placed on the vibration shaker and the magnetic mass is fixed to a stationary structure, namely piezoelectric beam with stationary magnet (PSM) system. While in Fig. 1(b), both the piezoelectric cantilever beam and the fixed magnet will be placed under the same vibration source applying the same base excitations, namely piezoelectric cantilever under the same vibration (PVM) system.

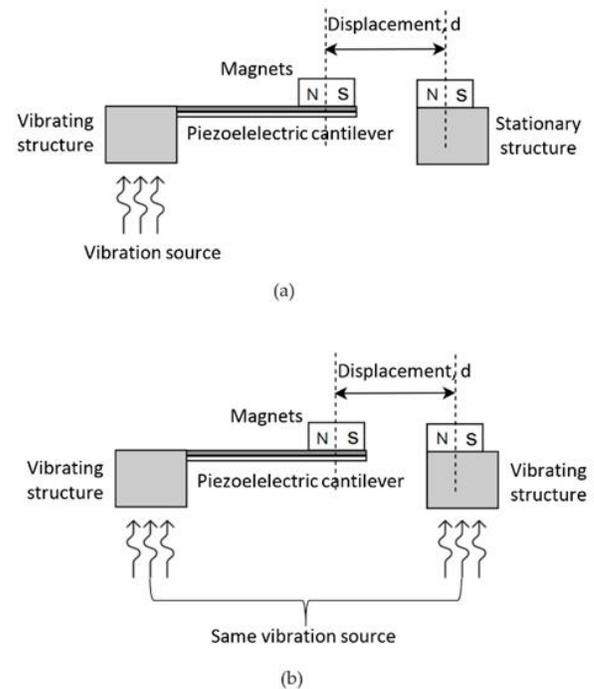


Fig. 1. Setup of Piezoelectric Energy Harvester for (a) PSM (b) PVM.

In electromechanical modeling, a linear resonant piezoelectric harvester can be represented based on Euler-Bernoulli beam equation. In Fig. 1, if the magnets are taken out and replaced with a similar sized mass, the piezoelectric harvester becomes a linear system that can be described using the governing electromechanical model, as in (1) and (2).

$$M\dot{x}'(t) + Cx'(t) + Kx(t) - \theta v(t) = F(t) \quad (1)$$

$$C_p \dot{v}(t) + \frac{v(t)}{R} + \theta \dot{x}(t) = 0 \quad (2)$$

Where M and C denotes the total mass and damping experienced by the energy harvester respectively. K and θ characterize the effective stiffness and the equivalent linear piezoelectric electromechanical coupling coefficient. C_p characterizes the corresponding capacitance of the piezoelectric substance and $v(t)$ denotes the voltage across the external load resistance, R . The vertical tip displacement of the mass is represented by $x(t)$ while $F(t)$ is force mechanically induced by the surrounding vibration excitation [40-42].

When the proof mass of the energy harvester is interchanged with magnets and arranged in repulsive mode, a magnetic repulsive force, F_m exists between the magnets and eventually changes the linear system defined by (1) and (2) to be magnetically coupled non-linear piezoelectric harvester. The non-linear energy harvesting system can then be described, as in (3) and (4).

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) - \theta v(t) = F(t) + F_m \quad (3)$$

$$C_p \dot{v}(t) + \frac{v(t)}{R} + \theta \dot{x}(t) = 0 \quad (4)$$

Where the nonlinear magnetic force, F_m can be articulated as the polynomial equation of.

$$F_m = \mu x(t) + \lambda x^3(t) \quad (5)$$

B. Effect of Distance on Interaction between Magnets

Since the stiffness of the piezoelectric cantilever beam is dependent on the magnetic force in the system, the position and distance between magnets will also be one of the factors that will determine the energy harvester performance. In order to create bistability, two magnets are placed in opposite polarity with a specific distance, d along the x -axis of the beam as illustrated in Fig. 2. Due to the magnetic repulsive force, F_m amid the magnets, the actual bending of the beam tip can be characterized as the vertical displacement, h of the tip mass.

Theoretically, a magnetic repulsive force, F_m exists between the magnets and its magnitude will decrease as the distance, d between the magnet increases. In order to observe the impact of this repulsive force on the system, a simplified lumped parameter model is used to represent the physical system as well as to approximate the effect of distance to the respective force as shown in Fig. 3.

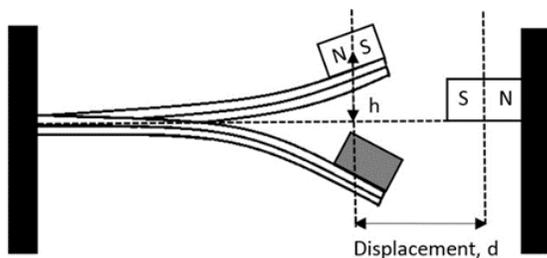


Fig. 2. A Piezoelectric System with Adjustable Distance between Magnets.

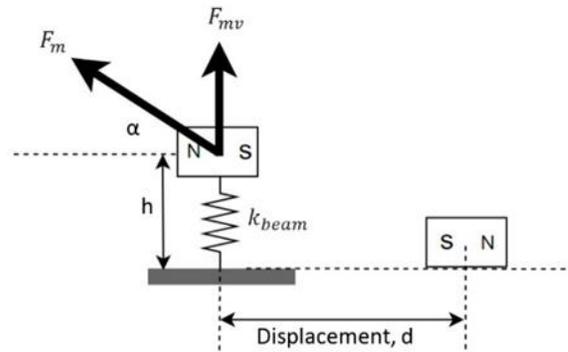


Fig. 3. A Simplified Lumped Parameter Model for the Piezoelectric System.

The total mass, m of the energy harvester system is determined by the effective mass of the first flexural mode of the beam plus the magnetic mass, while the effective spring stiffness, k denotes the elastic response of the piezoelectric cantilever beam [40]. The repulsive force, F_m is assumed to have a constant magnitude for a given value of distance, d provided that the angle θ is reasonably small. Thus, as the mass on the cantilever tip moves, the repulsive force, F_m changes in the direction by an angle α . Since the longitudinal stiffness of the piezoelectric cantilever is assumed to be adequately high, the horizontal component of the repulsive force, F_m will be balanced off. The vertical component of the repulsive force, F_{mv} which affects the stiffness and motion of the energy harvester can be described as.

$$F_{mv} = F_m \sin \alpha \quad (6)$$

The distance, d between the magnets and its relation to the vertical mass displacement, h can be written as.

$$h = d \tan \alpha \quad (7)$$

Consequently, the resultant relationship between the distance, d and the vertical constituent of the repulsive force, F_{mv} can be further deduced as.

$$F_{mv} = F_m \sin \alpha = F_m \frac{h}{\sqrt{d^2 + h^2}} \quad (8)$$

Applying Taylor series expansion around $x=0$ up to the third term, the vertical force, F_{mv} can be represented as.

$$F_{mv} \cong \frac{F_m}{d} x - \frac{F_m}{2d^3} x^3 \quad (9)$$

It is noted that the vertical force, F_{mv} is a nonlinear third order polynomial function which matches the assumption earlier for magnetic response cantilever system. From the derived equations, it is observed that as the distance, d increases, the vertical force, F_{mv} will decrease accordingly. Since the repulsive force, F_m is also a function of distance, d , this simply indicates that as the relative distance between the magnets decreases, the resultant magnetic force applied on the cantilever system increases and hence the potential energy of the energy harvesting system will change accordingly.

As the mass, m being repositioned from its equilibrium point, the total force, F_{total} acting on the mass, m as shown in

Fig.3 will be the summation of the spring restoring force, F_s and the counter-restoring vertical force, F_{mv} that is described as.

$$F_{total} = F_s + F_{mv} = -k_{beam}x + \frac{F_m}{d}x - \frac{F_m}{2d^3}x^3 \quad (10)$$

The potential energy, $E(x)$ of the energy harvesting system is then deduced as.

$$E(x) = - \int F_{total} dx = \frac{1}{2} \left(k_{beam} - \frac{F_m}{d} \right) x^2 + \frac{F_m}{8d^3} x^4 \quad (11)$$

As the distance between the magnets increases, it is perceived that the repulsive magnetic force, F_m will also be reduced significantly and when it decreases until zero, the energy harvesting system will become a linear system. Fig. 4 shows the graph for potential energy, $E(x)$ of the energy harvesting system for diverse values of repulsive magnetic force per distance.

When the repulsive magnetic force per distance is less than or equal to the cantilever beam stiffness, k_{beam} , the potential energy, $E(x)$ of the energy harvester will have only one stable equilibrium position at its origin. In this circumstance, the system is said to be working under monostable condition and is still characterized under linear system. As the repulsive magnetic force per distance increases and exceeds the cantilever beam stiffness, k_{beam} , the potential energy, $E(x)$ will exhibit a bistable behavior whereby a symmetric double well with an unstable equilibrium position at the origin and two stable equilibrium positions exist within the energy harvester. When the system is working under bistable condition, the cantilever beam will oscillate within the stable equilibrium positions in each energy well as it will interchange from one equilibrium state to another when the external vibration energy is sufficiently high.

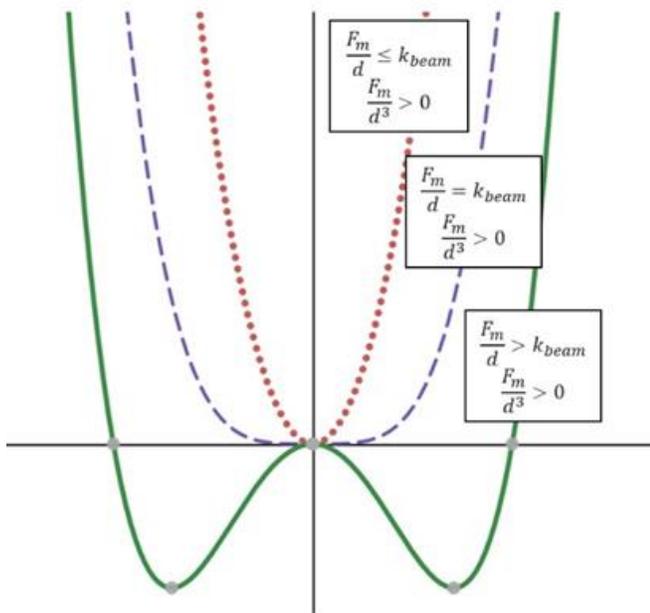


Fig. 4. Potential Energy, $E(x)$ for Monostable and Bistable Conditions.

The change in the potential energy of the cantilever beam basically results in a monostable or bistable characteristics in the energy harvesting system allowing the system to work differently based on the diverse requirements in the vibration environment. If the system is working under bistable behavior, the cantilever beam is able to switch between two equilibrium states, thus expanding the possibility of harvesting energy in a wider spectrum of vibrational frequency. Therefore, in order to achieve bistability in the system, the distance between the magnets should be sufficiently low enough to achieve the condition where the repulsive magnetic force per distance exceeds the stiffness of the cantilever beam, k_{beam} .

C. Effect of Magnetic Stiffness on Resonance Frequency

For a linear piezoelectric harvester with effective mass, m , the resonant frequency of the linear energy harvesting system can be described as.

$$\omega_{beam} = \sqrt{\frac{k_{beam}}{m}} \quad (12)$$

When the tip mass is replaced with a magnet and the energy harvesting system is deliberated as presented in Fig. 1, the resultant magnetic force will vary the stiffness of the cantilever beam, k_{beam} resulting in a change of resonance frequency. Consequently, the resonance frequency of the energy harvester will now be dependent on the stiffness linked to the magnetic force as well as the rigidity of the cantilever beam. The effective stiffness and the weight of the magnet will essentially determine the resonant frequency of the energy harvesting system. In order to parametrically model the influence of the magnetic strength and spectrum on the stiffness of the cantilever beam, a lumped parameter model was proposed to characterize the nonlinear system.

Fig. 5 illustrates the lumped parameter model of the nonlinear energy harvesting system as a consequence of additional stiffness acquainted with the repulsive magnetic force. The resultant force contributed by the repulsive magnetic force is demonstrated as a variable spring where the stiffness of the spring is subjected to the variation of the magnetic force with respect to the relative distance between both of the magnets.

As a result, the total effective stiffness and its resonant frequency of the energy harvester can be further deduced as

$$K_{eff} = K_{beam} + K_{magnet} \quad (13)$$

$$\omega_{eff} = \sqrt{\frac{K_{eff}}{m_{eff}}} \quad (14)$$

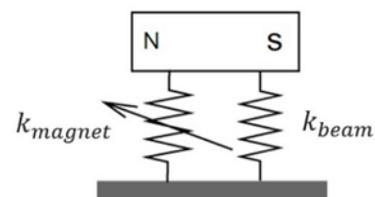


Fig. 5. Lumped Parameter Model for Nonlinear Energy Harvesting System.

Theoretically, as the magnetic force on the beam increases, the stress/strain imposed on the cantilever beam will also increase accordingly. Consequently, the resonance frequency will also change depending on the attractive or repulsive mode of the magnets and the resultant stiffness at the mass tip of the cantilever. It should be noted that stress induced by the magnets should not be larger than the yield stress of the beam for repulsive magnetic mode. By deducing the equations, one can tune the desired resonant frequency, ω_{tuned} from the original beam frequency, ω_{beam} of the energy harvester by determining the appropriate magnetic stiffness using the equation.

$$K_{magnet} = m_{eff}\omega_{tuned}^2 - K_{beam} = m_{eff}(\omega_{tuned}^2 - \omega_{beam}^2) \quad (15)$$

III. RESULT AND DISCUSSION

A. Design of Experiment

To assess the feasibility of the nonlinear energy harvester, a prototype of the system was built and verified in the laboratory. Fig. 6 shows the apparatus and design of the experimental structure for the energy harvesting system. The vibration shaker was used to produce the controllable vibration base excitation to the whole system throughout the experiment. A piezoelectric strip with dimensions of 1.25 x 0.5 x 0.02 inch, weighing 1.372 gram was used as the cantilever beam in the system. Fig. 7 illustrates the dimension of the piezoelectric cantilever applied throughout the experiment. A permanent magnet weighing 0.75 gram was secured at the free end tip of the cantilever beam while another magnet with opposing polarity was fixed on an external stationary structure with the purpose to adjust the distance between the magnets. The magnets were arranged in repulsive mode and were displaced in the direction of x -axis.

The empirical study of the bistable energy harvesting system was divided into two classifications. The initial part of the experiment comprises of analysis on the effect of the spacing displacement, d between two of the repulsive magnets on the resonant frequency of the system. In the subsequent experiment, the performance in terms of voltage output of the piezoelectric energy harvester was further examined according to the variety of the relative distance between the two repulsive magnets. Through the variation of distance between the magnetic mass, the stiffness of the cantilever beam can be regulated to obtain the desired frequency range. As the relative displacement between both of the repulsive magnets decreases, the stationary location of the cantilever beam changes accordingly. The variation of stationary point is reliant on the extent of hardening influence on the piezoelectric cantilever as the relative displacement between the two repulsive magnets changes.

Furthermore, as discussed in the previous sections, both of these experiments were done under two different circumstances scenarios. One of the scenarios involves pairing of the static magnetic mass under stationary condition while another scenario involves pairing of the static magnetic mass under similar vibration source, as depicted in Fig. 1. The frequency response curve for both scenarios was investigated respectively. The impact of spacing displacement on the magnetic force that affects the bistability of the energy harvesting system was also observed accordingly.

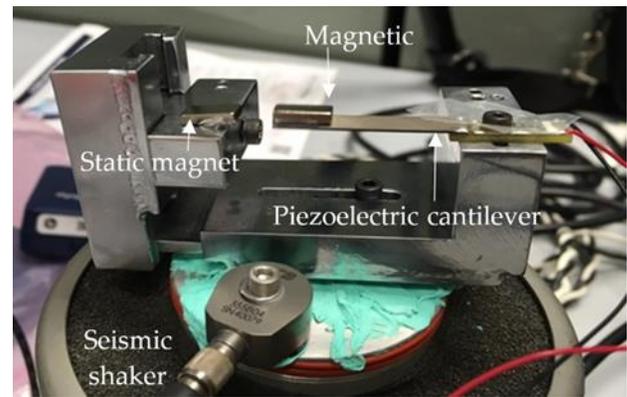


Fig. 6. Design of Experiment Apparatus of the Piezoelectric Energy Harvester.

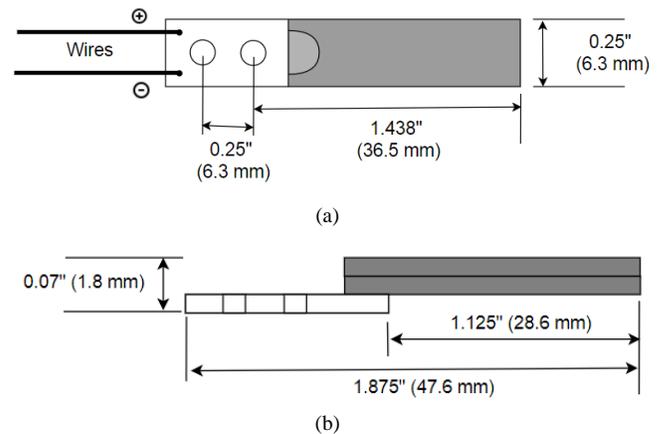


Fig. 7. Dimension of the Piezoelectric Cantilever Beam (a) Top View (b) Side View.

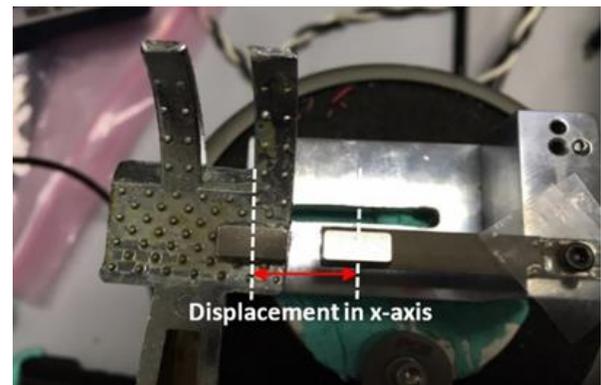


Fig. 8. Top View of Experiment Apparatus of the Piezoelectric Energy Harvester with Displacement in x -axis.

Fig. 8 illustrates the top view of the apparatus setup with horizontal spacing displacement in x -axis between the two magnets. For this setup, the energy harvester involves pairing of the static magnetic mass under stationary condition. During the experiment, the static magnet was adjusted and move away from the piezoelectric cantilever beam to observe the impact of magnetic force on the system. The spacing displacement between the magnets was measured from the center of the respective repulsive magnets.

B. Effect of Spacing Displacement on Resonant Frequency

An analysis on the effect of applying magnetic forces in the adjustment of the resonance frequency of the energy harvesting system has been investigated as follows. In the first part of the experiment, the fixed magnet is placed under stationary condition to observe the influence on the resonant frequency of the energy harvester as presented in Fig. 1(a). The static magnet is then displaced along the x -axis, making sure there is no displacement in the y -axis and z -axis between the two repulsive magnets in the system. The deviations of the resonant frequency as a function of spacing distance for PSM system is then plotted as presented in Fig. 9(a). Based on the observation, as the magnets were moved closer to each other from large distances, the system tends to behave as monostable linear system with decreasing resonance frequency until it reaches the condition where the repulsive magnetic force per distance, exceeds the stiffness of the cantilever beam, k_{beam} . Subsequent to this condition, when the magnets are pushed further and are sufficiently close, the resonant frequency tend to increase drastically creating bistability condition for the system. In this circumstance, the system has the ability to interchange between two equilibrium states and the fluctuation of the tip displacement can surge substantially if the base excitation level is increased sufficiently.

Further analysis on the PSM system results shows that for spacing displacement above 8 mm as in region IV, the resonant frequency of the energy harvesting system tends to stabilize, indicating the waning of repulsive force by the magnets. As the relative displacement between the magnets decreases, the resonant frequency of the system seems to decrease accordingly, as shown in region III. It is also observed that for displacement ranges between 3 mm and 4 mm (region II), there is a sharp decrease of resonant frequency up to its minimum frequency of 114 Hz. It is then followed by a sharp increase of resonant frequency (region I) as we decrease the spacing displacement, placing the magnets into stronger repulsive mode. As the strength of the repulsive magnet force increases, the piezoelectric cantilever beam responded accordingly through the change in its static position and bending effect, subsequently triggering a drastic adjustment in the resonant frequency response. At this point, the energy harvester will be working under bistable condition. Thus, the resultant analysis displays that in order to ensure that the energy harvesting system is working under bistable mode; the minimum requirement for the distance between the repulsive magnets is less than 3 mm.

In the second part of the experiment, the fixed magnet is placed under the same vibration source as the piezoelectric cantilever beam to observe the effect on its resonant frequency as demonstrated in Fig. 1(b). Fig. 9(b) illustrates the variations of the resonant frequency when the spacing distance between two magnets is altered accordingly under the common vibration source for PVM system. It is observed that a similar pattern of resonant frequency is obtained in comparison with the PSM system. However, the change of resonant frequency may not be as abrupt compared to the static magnetic mass

under stationary condition. Based on the analysis, the resonant frequency of the system stabilizes as the distance between both magnets increases above 6mm, as shown in region III. As we move the magnets to closer to each other, the resonant frequency of the PVM system decreases gradually for distances between 4 mm to 6 mm (region II). In this setup, the energy harvesting system began to function as a bistable system for magnetic distances below 4 mm (Region I).

For the significance of this investigation, it is perceived that the repulsive influence between the magnets tend to stabilize only at displacement beyond 6 mm for the energy harvesting system. For relatively smaller distance of the spacing displacement, the increase of hardening influence between the magnets causes further bending effect on the cantilever and thus creates bistability of the resonant frequency in the system. In comparison between both of the systems, the PVM system seems to provide more feasible design for the energy harvester and it was able to achieve its bistability mode for larger threshold distance between magnets. This proves that the design of the nonlinear energy harvester should include the effect of vibration source on both the piezoelectric cantilever beam as well as the fixed magnet on the external structure.

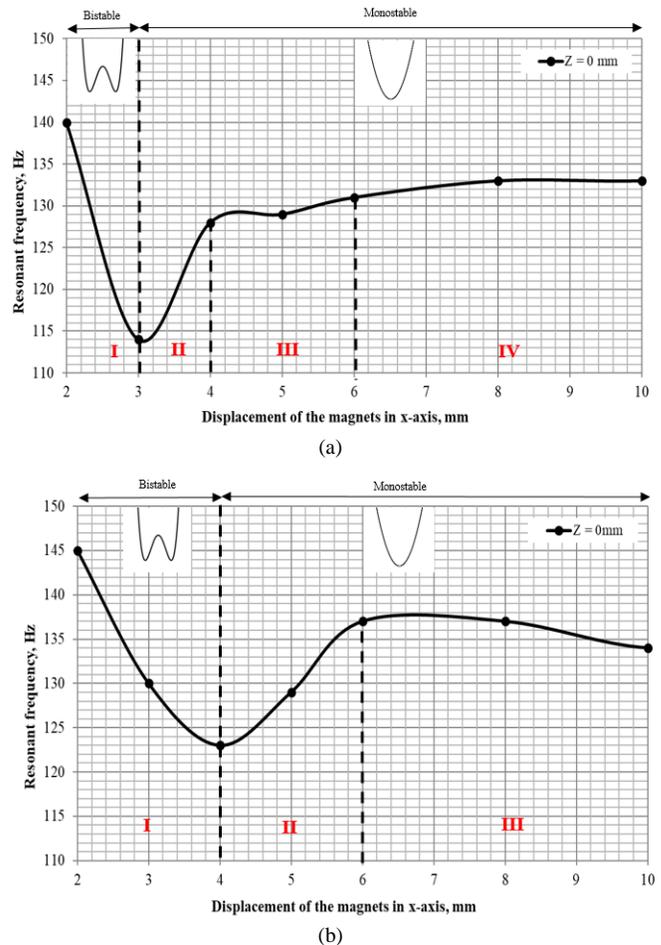


Fig. 9. Resonant Frequency of the Energy Harvester for different the Spacing Displacement, d for Static Magnetic Mass under (a) PSM (b) PVM.

Furthermore, the resultant graph for both experiments are also consistent with the theoretical expectations, endorsing that the cantilever beam leaps between two stable states for sufficiently close magnetic distance and adequate base excitation as demonstrated in Fig. 4. This change in resonance frequency due to the spacing displacement of the magnets was also found to have similar pattern as other researchers' work [43, 44]. However, in comparison with the other researchers' work, it was found that the addition of vibration source on the external magnet increases the region of bistability for the energy harvester. The resonance frequency of piezoelectric cantilever for the energy harvester with same vibration source also increases in comparison with the stationary magnet due to the impact of vibration on the coupling between the magnets.

These findings are substantially vital during the design considerations for vibration energy harvester and notable for researchers in this field of research.

C. Effect of Spacing Displacement on Output Voltage

A similar setup as presented in Fig. 1 was applied to measure and verify the performance of the nonlinear energy harvester in terms of open-circuit output voltage. The energy harvester was excited by a controllable vibration shaker with mechanical vibrations and placed accordingly using both scenarios as discussed in Section II. The excitation level of the shaker is set sufficiently low to prevent initiation of bistable mode as the distance between the magnets becomes substantially close. Consequently, the energy harvester was held to oscillate at only one interwell equilibrium state throughout the experiment. The function generator and amplifier was used to regulate the vibration shaker in tuning the resonance frequency for each cantilever beams. The output electrical responses were observed using the oscilloscope and its frequency response curve are plotted accordingly.

The resultant graph will also include the voltage output of the linear system with proof mass for comparison purposes. Fig. 10 illustrates the frequency response output of the open-circuit root mean square (rms) voltage generated by the energy harvester for a variation of relative displacement between the magnets for the PSM and PVM system. The differences in the output voltage were compared to observe the impact of magnetic force and location of vibration source on the cantilever beam. Based on our observation, the results showed that the relative displacement between the two magnets significantly affects the level of the harvested voltage. It is also eminent that the positioning of the vibration source on the piezoelectric cantilever and/or permanent magnets impacts the frequency response curves especially in terms broadening the frequency range of the energy harvester.

Fig. 10 shows that the relative distance between the two magnets significantly affects the level of the harvested voltage. It is also observed that by changing the relative displacement, the energy harvesting system has the competence to harvest vibrational energy in a wider spectrum of operating frequency. For the spacing displacement of $d=2\text{mm}$ as presented in Fig. 10(a) and Fig. 10(b), since the magnets were placed essentially close to each other, both of the PSM and PVM systems are now under bistable conditions. At this point, the magnetic field strength applied on the system was very high and the nonlinear

characteristics will be substantially visible as the excitation level of the vibration source increases. However, the effect of magnet on the piezoelectric cantilever causes the output voltage to drop significantly lower than its other counterparts. The resultant bandwidth for both of the system is also lower and does not provide a good model for broadband energy harvesting.

For the spacing displacement of $d=3\text{mm}$ as shown in Fig. 10(a), the PSM system was operating at its lowest resonance frequency as discussed in the previous section. In this case, both PSM and PVM systems are still operating in bistable conditions. However, the PSM system tends to exhibit broader frequency range as compared to the linear system and its other counterparts. Similarly, at the spacing displacement of $d=4\text{mm}$ for PVM system as shown in Fig. 10(b), where PVM was also operating at its lowest resonance frequency, the output voltage and its bandwidth are significantly higher than its counterparts of different spacing distances. In other words, in designing a bistable system, the optimal spacing distance to be chosen is when the resonant frequency of the cantilever beam is at its lowest point. The magnets were displaced further at spacing distance of 5 mm and above. The frequency response curves in Fig. 10(a) show that the output voltage of the PSM system decreases and remain fluctuating around the similar output voltage accordingly. Similarly, at Fig. 10(b), the output voltage remains constantly the same for spacing distance of 6mm and above.

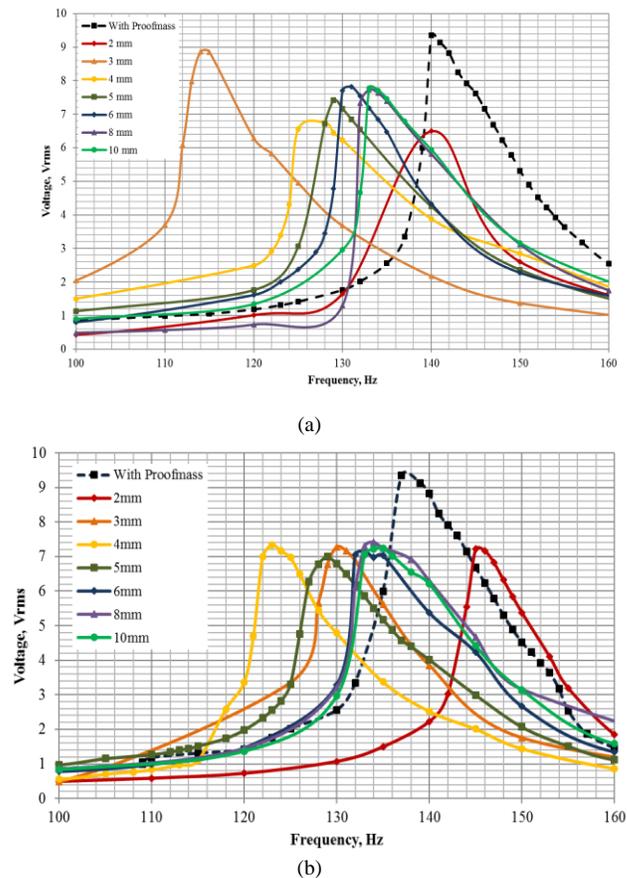


Fig. 10. Output Voltage of the Energy Harvester for different the Spacing Displacement, d for Static Magnetic Mass under (a) PSM (b) PVM.

These outputs indicate that both the PSM and PVM system were not affected significantly by the repulsive force of the magnets and thus regardless of the position of the vibration source, both system exhibits similar frequency response curve. However, it is noticeable that the output voltage for both PSM and PVM system is slightly lower in comparison with the linear system with proof mass and yet it has similar spectrum of frequency range in the frequency response curves.

As can be perceived from the experimental figures, with the decrease of spacing distance between the magnets, the impact of magnetic force intensifies and thus increases the hardening response of the piezoelectric cantilever. This notion of experiment indicated the ability of the energy harvesting system to shift from linear to nonlinear system gradually using permanent magnets. The results also showed that the position of vibration source affects the resonance frequency as well as the operating frequency of the energy harvesting system. Note that as the spacing distance was decreased to its minimal length, the frequency response did not provide the best bandwidth for PVM system. This indicates that as the magnetic force increases, the increased hardening response in the piezoelectric cantilever can cause reduction in bandwidth and eventually may not provide the widest possible range of operating frequency to harvest the vibrational energy. Thus, it is essential to note that the relative distance between two repulsive magnets as well as the positioning of vibration source can directly affect the resonant frequency and the operational range of frequency spectrum of the energy harvester.

IV. CONCLUSION

In this paper, the concept of bistable piezoelectric energy harvesting system by exploiting the effect of magnetic force was presented. Detailed investigation on the effect of the horizontal spacing distance between two magnets of repulsive mode in a piezoelectric energy harvester has also been deliberated. The impact of positioning the vibration source on either the piezoelectric cantilever beam only or both the piezoelectric cantilever beam and external magnets was compared in terms of resonance frequency and bandwidth of the operating frequency for broadband energy harvesting. It is shown that the model is feasible and applicable in harvesting energy in a wider band of frequency spectrum from ambient mechanical vibrations. Likewise, it is also established that the fundamental resonant frequency of the cantilever beam has significant dependence on the variations of relative distance between the magnets as well as the positioning of vibration source on the external magnets.

This paper shows that the piezoelectric energy harvester can be envisioned to accomplish wideband frequency energy harvesting by selecting the optimal spacing distance between two repulsive magnets. Alteration of spacing displacement can also be used to adjust the resonant frequency of the harvester for matching of surroundings excitation frequency in the environment.

V. FUTURE WORK

As a continuation of this research, further work on the impact of different sizes and locations of the magnets on the cantilever beam can be considered. The size of the magnets

may impart a different magnetic force towards the stress and strain of the cantilever beams and is therefore noteworthy for future work considerations. Furthermore, multiple piezoelectric beams with magnets and different configurations can also be worked upon for further considerations in increasing the bandwidth of the vibration energy harvesting system.

ACKNOWLEDGMENT

The authors would like to express gratitude and sincere appreciation to the Ministry of Higher Education of Malaysia for the financial support through Fundamental Research Grant Scheme (FRGS/1/2020/TK0/MMU/03/13). The authors would also like to acknowledge the Faculty of Engineering and Technology, Multimedia University and Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka for the support given in conducting this research.

REFERENCES

- [1] J. Kim, A. S. Campbell, B. E. F. de Ávila, and J. Wang, "Wearable biosensors for healthcare monitoring," *Nat. Biotechnol.*, vol. 37, no. 4, pp. 389–406, April 2019. <https://doi.org/10.1038/s41587-019-0045-y>.
- [2] A. E. Akin-Ponnle and N. B. Carvalho, "Energy Harvesting Mechanisms in a Smart City—A Review," *Smart Cities*, vol. 4, no. 2, pp. 476–498, April 2021. <https://doi.org/10.3390/smartcities4020025>.
- [3] J. Curry and N. Harris, "Powering the environmental Internet of Things," *Sensors*, vol. 19, no. 8, pp.1940, April 2019. <https://doi.org/10.3390/s19081940>.
- [4] A.A.A. Zayed, S.F.M. Assal, K. Nakano, T. Kaizuka, and A.M.R. Fath El-Bab, "Design Procedure and Experimental Verification of a Broadband Quad-Stable 2-DOF Vibration Energy Harvester," *Sensors*, vol. 19, pp. 2893, 2019. <https://doi.org/10.3390/s19132893>.
- [5] A. Kumar, S.F. Ali, and A. Arockiarajan, "Exploring the benefits of an asymmetric monostable potential function in broadband vibration energy harvesting," *Appl. Phys. Lett.*, vol. 112, pp. 233901, 2018. <https://doi.org/10.1063/1.5037733>.
- [6] M.G. Kang, W.S. Jung, C.Y. Kang, and S.J. Yoon, "Recent Progress on PZT Based Piezoelectric Energy Harvesting Technologies," *Actuators*, vol. 5, no. 1, pp. 5, 2016. <https://doi.org/10.3390/act5010005>.
- [7] K. Li, X. He, X. Wang, and S. Jiang, "A Nonlinear Electromagnetic Energy Harvesting System for Self-Powered Wireless Sensor Nodes," *J. Sens. Actuator Netw.*, vol. 8, pp. 18, 2019. <https://doi.org/10.3390/jsan8010018>.
- [8] S. Mohammadi and A. Esfandiari, "Magnetostrictive vibration energy harvesting using strain energy method," *Energy*, vol. 81, pp. 519–525, 2015. <https://doi.org/10.1016/j.energy.2014.12.065>.
- [9] S. Priya, H. Song, Y. Zhou, R. Varghese, A. Chopra, S. Kim, I. Kanno, L. Wu, D. Ha, J. Ryu, and R. Polcawich, "A Review on Piezoelectric Energy Harvesting: Materials, Methods, and Circuits," *Energy Harvest. Syst.*, vol. 4, pp. 3–39, 2017. <https://doi.org/10.1515/ehs-2016-0028>.
- [10] G. Scarselli, F. Nicassio, F. Pinto, F. Ciampa, O. Iervolino, and M. Meo, "A novel bistable energy harvesting concept," *Smart Mater Struct.*, vol. 25, pp. 055001, 2016. <https://doi.org/10.1088/0964-1726/25/5/055001>.
- [11] S.E. Jo, M.S. Kim, and K.J. Kim, "A resonant frequency switching scheme of a cantilever based on polyvinylidene fluoride for vibration energy harvesting," *Smart Mater Struct.*, vol. 21, pp. 015007, 2011. <https://doi.org/10.1088/0964-1726/21/1/015007>.
- [12] A. H. Alameh, M. Gratuze, and F. Nabki, "Impact of geometry on the performance of cantilever-based piezoelectric vibration energy harvesters," *IEEE Sens. J.*, vol. 19, pp. 10316–10326, 2019. <https://doi.org/10.1109/JSEN.2019.2932341>.
- [13] A. Hajati and S.G. Kim, "Ultra-wide bandwidth piezoelectric energy harvesting," *Appl. Phys. Lett.*, vol. 99, pp. 083105, 2011. <https://doi.org/10.1063/1.3629551>.
- [14] S. Zhou, W. Chen, M.H. Malakooti, J. Cao, and D.J. Inman, "Design and modeling of a flexible longitudinal zigzag structure for enhanced

- vibration energy harvesting,” *J Intell Mater Syst Struct.*, vol. 28, pp. 367-380, 2017. <https://doi.org/10.1177/1045389X16645862>.
- [15] S. Kumar, A. Mitra, and H. Roy, “Geometrically nonlinear free vibration analysis of axially functionally graded taper beams,” *Int. J. Eng. Sci. Technol.*, vol. 18, pp. 579-593, 2015. <https://doi.org/10.1016/j.jestch.2015.04.003>.
- [16] Y. Uzun and E. Kurt, “The effect of periodic magnetic force on a piezoelectric energy harvester,” *Sens. Actuator A Phys.*, vol. 192, pp. 58-68, 2013. <https://doi.org/10.1016/j.sna.2012.12.017>.
- [17] J. Jiang, S. Liu, L. Feng, and D. Zhao, “A review of piezoelectric vibration energy harvesting with magnetic coupling based on different structural characteristics,” *Micromachines*, vol. 12, pp. 436, 2021. <https://doi.org/10.3390/mi12040436>.
- [18] J. Liang, “Synchronized bias-flip interface circuits for piezoelectric energy harvesting enhancement: A general model and prospects,” *J Intell Mater Syst Struct.*, vol. 28, pp. 339-356, 2017. <https://doi.org/10.1177/1045389X16642535>.
- [19] E. Lefeuvre, A. Badel, A. Brenes, S. Seok, and C.S. Yoo, “Power and frequency bandwidth improvement of piezoelectric energy harvesting devices using phase-shifted synchronous electric charge extraction interface circuit,” *J Intell Mater Syst Struct.*, vol. 28, pp. 2988-2995, 2017. <https://doi.org/10.1177/1045389X17704914>.
- [20] M.R. Mhetre and H.K. Abhyankar, “Human exhaled air energy harvesting with specific reference to PVDF film,” *Int. J. Eng. Sci. Technol.*, vol. 20, pp. 332-339, 2017. <https://doi.org/10.1016/j.jestch.2016.06.012>.
- [21] Z. Lin, J. Yang, J. Zhao, N. Zhao, J. Liu, Y. Wen, and P. Li, “Enhanced broadband vibration energy harvesting using a multimodal nonlinear magnetoelectric converter,” *J. Electron. Mater.*, vol. 45, pp. 3554–3561, 2016. <https://doi.org/10.1007/s11664-016-4531-4>.
- [22] Y. Cheng, N. Wu, and Q. Wang, “An efficient piezoelectric energy harvester with frequency self-tuning,” *J. Sound Vib.*, vol. 396, pp. 69-82, 2017. <https://doi.org/10.1016/j.jsv.2017.02.036>.
- [23] Y.-H. Shin, J. Choi, S.J. Kim, S. Kim, D. Maurya, T.-H. Sung, S. Priya, C.-Y. Kang, and H.-C. Song, “Automatic resonance tuning mechanism for ultra-wide bandwidth mechanical energy harvesting,” *Nano Energy*, vol. 77, pp. 104986, 2020. <https://doi.org/10.1016/j.nanoen.2020.104986>.
- [24] M. Lallart, S.R. Anton, and D.J. Inman, “Frequency self-tuning scheme for broadband vibration energy harvesting,” *J Intell Mater Syst Struct.*, vol. 21, pp. 897-906, 2010. <https://doi.org/10.1177/1045389X10369716>.
- [25] L. Yu, L. Tang, and T. Yang, “Piezoelectric passive self-tuning energy harvester based on a beam-slider structure,” *J. Sound Vib.*, vol. 489, pp. 115689, 2020. <https://doi.org/10.1016/j.jsv.2020.115689>.
- [26] W. Yang and S. Towfighian, “A parametric resonator with low threshold excitation for vibration energy harvesting,” *J. Sound Vib.*, vol. 446, pp. 129-143, 2019. <https://doi.org/10.1016/j.jsv.2019.01.038>.
- [27] M. Lallart, C. Richard, L. Garbuio, L. Petit, and D. Guyomar, “High efficiency, wide load bandwidth piezoelectric energy scavenging by a hybrid nonlinear approach,” *Sens. Actuator A Phys.*, vol. 165, pp. 294-302, 2011. <https://doi.org/10.1016/j.sna.2010.09.022>.
- [28] Z. Yi, Y. Hu, B. Ji, J. Liu, and B. Yang, “Broad bandwidth piezoelectric energy harvester by a flexible buckled bridge,” *Appl. Phys. Lett.*, vol. 113, pp. 183901, 2018. <https://doi.org/10.1063/1.5049852>.
- [29] D. Gibus, P. Gasnier, A. Morel, F. Formosa, L. Charleux, S. Boisseau, G. Pillonnet, C.A. Berlitz, A. Quelen, and A. Badel, “Strongly coupled piezoelectric cantilevers for broadband vibration energy harvesting,” *Appl. Energy*, vol. 277, pp. 115518, 2020. <https://doi.org/10.1016/j.apenergy.2020.115518>.
- [30] R.M. Toyabur, M. Salauddin, and J.Y. Park, “Design and experiment of piezoelectric multimodal energy harvester for low frequency vibration,” *Ceram. Int.*, vol. 43, pp. S675-S681, 2017. <https://doi.org/10.1016/j.ceramint.2017.05.257>.
- [31] E. Dechant, F. Fedulov, D.V. Chashin, L.Y. Fetisov, Y.K. Fetisov, and M. Shamonin, “Low-frequency, broadband vibration energy harvester using coupled oscillators and frequency up-conversion by mechanical stoppers,” *Smart Mater Struct.*, vol. 26, pp. 065021, 2017. <https://doi.org/10.1088/1361-665X/aa6e92>.
- [32] P. Li, S. Gao, X. Zhou, H. Liu, and J. Shi, “Analytical modeling, simulation and experimental study for nonlinear hybrid piezoelectric---electromagnetic energy harvesting from stochastic excitation,” *Microsyst. Technol.*, vol. 23, pp. 5281–5292, 2017. <https://doi.org/10.1007/s00542-017-3329-5>.
- [33] C. Lan and W. Qin, “Enhancing ability of harvesting energy from random vibration by decreasing the potential barrier of bistable harvester,” *Mech Syst Signal Process.*, vol. 85, pp. 71-81, 2017. <https://doi.org/10.1016/j.ymsp.2016.07.047>.
- [34] W. Wang, J. Cao, C.R. Bowen, D.J. Inman, and J. Lin, “Performance enhancement of nonlinear asymmetric bistable energy harvesting from harmonic, random and human motion excitations,” *Appl. Phys. Lett.*, vol. 112, pp. 213903, 2018. <https://doi.org/10.1063/1.5027555>.
- [35] H. Xingbao and B. Yang, “Improving energy harvesting from impulsive excitations by a nonlinear tunable bistable energy harvester,” *Mechanical Systems and Signal Processing*, vol. 158, pp. 107797, 2021. <https://doi.org/10.1016/j.ymsp.2021.107797>.
- [36] P. Deepak and B. George, “Piezoelectric energy harvesting from a magnetically coupled vibrational source,” *IEEE Sens. J.*, vol. 21, pp. 3831-3838, 2021. <https://doi.org/10.1109/JSEN.2020.3025216>.
- [37] Z. Ren, H. Zhao, C. Liu, L. Qian, S. Zhang, and J. Zhao, “Study the influence of magnetic force on nonlinear energy harvesting performance,” *AIP Advances*, vol. 9, pp. 105107, 2019. <https://doi.org/10.1063/1.5111848>.
- [38] P. Firoozy, S.E. Khadem, and S.M. Pourkiaee, “Broadband energy harvesting using nonlinear vibrations of a magnetopiezoelectric cantilever beam,” *Int. J. Eng. Sci.*, vol. 111, pp. 113–133, 2017. <https://doi.org/10.1016/j.ijengsci.2016.11.006>.
- [39] N. Jackson, “PiezoMEMS nonlinear low acceleration energy harvester with an embedded permanent magnet,” *Micromachines*, vol. 11, pp. 500, 2020. <https://doi.org/10.3390/mi11050500>.
- [40] M. Kim, M. Hoegen, J. Dugundji, and B.L. Wardle, “Modeling and experimental verification of proof mass effects on vibration energy harvester performance,” *Smart Mater. Struct.*, vol. 19, pp. 045023, 2010. <https://doi.org/10.1088/0964-1726/19/4/045023>.
- [41] A. Erturk and D.J. Inman, “An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations,” *Smart Mater. Struct.*, vol. 18, pp. 025009, 2009. <https://doi.org/10.1088/0964-1726/18/2/025009>.
- [42] S. Zhou, J. Cao, and J. Lin, “Theoretical analysis and experimental verification for improving energy harvesting performance of nonlinear monostable energy harvesters,” *Nonlinear Dyn.*, vol. 86, pp. 1599–1611, 2016. <https://doi.org/10.1007/s11071-016-2979-7>.
- [43] M. Ferrari, V. Ferrari, M. Guizzetti, B. Andò, S. Baglio, and C. Trigona, “Improved energy harvesting from wideband vibrations by nonlinear piezoelectric converters,” *Sens. Actuator A Phys.*, vol. 162, pp. 425-431, 2010. <https://doi.org/10.1016/j.sna.2010.05.022>.
- [44] V. Shah, R. Kumar, M. Talha, and J. Twiefel, “Numerical and experimental study of bistable piezoelectric energy harvester,” *Integr. Ferroelectr.*, vol. 192, pp. 38-56, 2018. <https://doi.org/10.1080/10584587.2018.1521669>.