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# Development of a Nonlinear Harvesting Mechanism from Wide Band Vibrations

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ABSTRACT

The main objective of this study is to present an energy harvesting approach to scavenge electrical energy from mechanically vibrated piezoelectric materials. A mechanical energy harvester device has been developed and tested. The fundamental benefit of this mechanical device is that it can function effectively in a wide range of ambient vibration frequencies, whereas traditional harvesters are limited. A suitable conditioning circuit for energy scavenging has been proposed which can achieve optimal power stream. For controlling the power flow into the battery a circuit has been designed consisting of an AC to DC rectifier, an output capacitor, a switch mode DC to DC converter, and an electromechanical battery. An adaptive control system has been described for switching any electronics devices and maximizing battery storage capacity. Experimental results reveal that the power transfer rate can be enhanced by approximately 400% by utilizing the adaptive DC to DC converter. Various investigations on the piezoelectric harvester have revealed that the energy generated by the mechanical device can exceed the 1.4-volt barrier, which is suitable for charging capacitors in electronics devices. The findings of this study will be crucial in mitigating society's energy crisis.



## 1. Introduction

Energy harvesting, often known as power harvesting, is a process of extracting energy. Energy can be harvested from a variety of ambient sources, including solar, wind, wave, biomass, vibration, and piezoelectric materials [1], [2].Vibration energy harvesting is the process of converting vibration energy into electrical energy. Energy harvesting through vibration is similar to energy harvesting from sound. Mechanical vibrations, electromagnetic induction, electrostatic, and Piezoelectric techniques can all be used to harvest energy from vibrations. In the vibration-powered generator, a resonator is employed to amplify the vibration source. The vibrations are converted into electrical energy using a mechanical piezoelectric transducer. A transducer can be composed of three main components, such as a coil, a piezoelectric crystal, and a magnet.

There is a link between the electrical and mechanical states in piezoelectric materials. The ability of a material to generate electric charge with the help of applied mechanical stress is known as direct piezoelectric effect, whereas the inverse piezoelectric effect occurs when the material is deformed owing to an electrical field. The use of a nonlinear harvester and a clamped-clamped beam could be an excellent approach for scavenging energy from vibration [3]. Piezoelectric materials can be used to convert mechanical vibrational energy into alternating current, which can then be converted to direct current for wireless applications or battery charging [4]. Piezoelectric materials are important due to their durability, dependability, and inexpensive cost. Energy can be scavenged from vibration in this energy collecting procedure. In recent years, ambient sources such as light, vibration, heat, radio waves, and others have become more appealing sources for generating power. Vibration can generate low amount of power. This low energy can be utilized in low-power electronics devices, such as low-power electronics, wireless sensor networks, and long-term low-power sensors that cannot be powered by batteries.

The contribution of renewable energy is increasing day by day tremendously to mitigate the power shortage of off grid rural area. The prominent trends of renewable energy sources such as vibration open up significant new business opportunities for the energy leaders. Therefore, The main goal of this study is the development of a solution for energy harvesting from wide band frequency of vibrations exploiting benefits from a nonlinear configuration. In particular, the harvester is designed with a bi-stable cantilever beam, one proof mass in the centre, two clampers at each end of the beam, and two piezoelectric transducers. Ambient vibrations of varied frequencies would initiate the beam switching in this mechanical piezoelectric transducer. The mechanical vibrations will be converted to electrical energy by a piezoelectric harvester. The goal of this study is to address the research questions in generating more renewable energy from vibrations that can be utilised to replace fossil fuels in a way that is both environmentally and economically viable. The mechanical device in this paper is novel in that it can gather energy at different frequencies of vibrations. The mechanical device shows nonlinearity in the form of a wide band. This study can be summarised as follows:

- To scavenge energy from varied frequency of vibrations, a piezoelectric transducer, also known as a mechanical vibration harvester, was designed.
- To assess the mechanical device's performance, two types of observations were performed: static and dynamic characteristics. the performance of the mechanical device, two types of observations were performed: static and dynamic characteristics.
- The effect of increasing frequency on voltage has been studied.

## 2. Mathematical Modelling

A typical energy harvester is composed of a resonant mechanical structure that is stimulated at a frequency that is extremely close to its resonance frequency. The proposed mechanical harvester, on the other hand, may operate at various vibration frequencies. Different types of energy harvesters have been tested for various frequencies in the literature, and different methods for energy scavenging have been discovered [5]. Various challenges still remain, including low efficiency, complex implementation, additional system requirements, and low power generation. In practise, using a nonlinear energy harvester has addressed all of the above obstacles [6].

In terms of the volume of energy emitted from wide band vibrations, it has been demonstrated that a nonlinear bi-stable system can outperform a linear harvester under the right conditions. With the help of pre-compression along the Y axis, a nonlinear bi-stable system can be achieved from the proper design of a mechanical device. The perpendicular stress at the surface of the clamped-clamped beam has resulted in a bi-stable behaviour. The beam snaps between its equilibrium states due to the mechanical stress of originating vibrations of diverse frequencies [7].

For the Snap-Through Buckling energy harvester, a classical second order differential equation of mass damper-spring system was used. The vibrations have been proven to produce a bi-stable potential energy function as an additive nonlinear term. The dynamical properties of the harvester were demonstrated using the nonlinear differential equation [8].

$$m\ddot{x} + \dot{x} - \psi(x) = F(t) \tag{1}$$

From the equation it can be said that, $F(t)$ is the external input of mechanical vibrations of different frequencies, $\psi(x)$ is the restoring force linked up with the function of potential energy, $d$ belongs to the damping coefficient and $\ddot{x}$, $\dot{x}$ and $x$ are, respectively, the acceleration, the velocity and the displacement of the cantilever beam.

$$\psi(x) = -\frac{\delta U(x)}{\delta(x)} \tag{2}$$

For describing the nonlinear mechanism of energy harvester, a quartic potential energy function has been adopted.

$$\delta U(x) = \frac{1}{4}ax^4 - \frac{1}{2}bx^2 \tag{3}$$

By considering the form of Eq. (3) and Eq. (1) the following equation (4) can be obtained

$$\ddot{x} + dx + ax^3 - bx = F(t) \tag{4}$$

For fitting this model, it has been used a scrip, in which there are some parameters like $J$, $a$, $b$. Here $J$ is the parameter which shows the difference between actual data from measurement and the reference data and demonstrated the value of $J$ must be small for getting good performance and parameters $a$ & $b$ used for identifying the model. $J$ is calculated using real ($F_{real}$) and predicted ($F_{pred}$) value of $F(t)$ as:

$$J = \sqrt[2]{\frac{\sum(F_{real} - F_{pred})^2}{\sum F_{real}^2}} \tag{5}$$

## 3. Experimental Set-up

For power generation, a basic beam with a proof mass and clamber was modelled and tested. At both ends of the clamper, a cantilever beam with bimorph configurations was attached. As a beam, thick film has been employed in the past. In this energy harvesting system, two piezoelectric materials (PZT) and one cantilever beam with a proof mass were used to improve frequency flexibility and bistable states. To show the harvester's features, two types of measurements were used: static and dynamic. A load cell and various masses were used to move the beam between two states by altering the pre-compression to see the static properties. To see the electrical response of DP-NLH, a repeated cycle of stimulation was used with a standard shaker. Initially, the shaker was moved by a sinusoidal periodic signal of variable frequency. In the second phase of the design, a "walking signal" was created by running at various frequencies ranging from low to high order.

A typical energy harvester performs well under harmonic excitation, which occurs when the natural frequency is well matched to the system's excitation frequency. In Fig. 1, an improved mechanical piezoelectric harvester is presented. The new piezoelectric harvester has been made by a proof mass that is mounted inside a beam, a cantilever beam, two clampers at both end of beam and two PZT. Cantilever beam are well suited using clampers in two end of it. When the cantilever bean is buckled, the mechanical harvester shows nonlinearity with two potential wells. Multiple solutions have been found from the harvester as this device works in different frequency of vibrations and beam jumps between the potential wells. Practically a bi-stable clamped- clamped beam has been used to see the

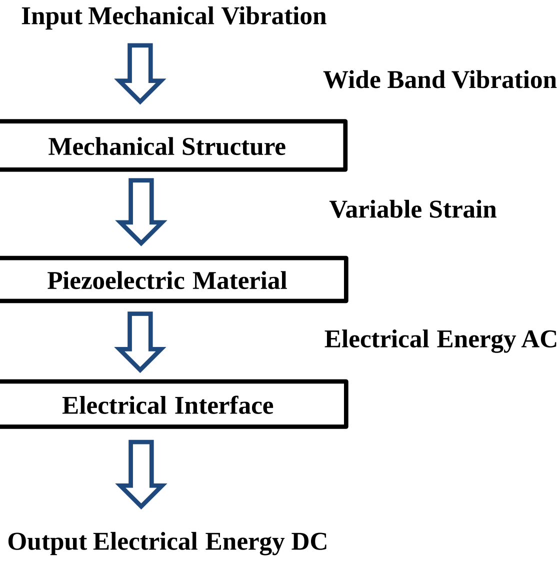



**Fig. 1.** Process flow diagram of energy harvesting from vibrations

low-cost solution for vibrational energy scavenging from wide band vibrations. Using vibration of ambient sources, beam switching has been activated between two states. The mechanical device has been used to convert the mechanical vibration to electrical energy due to the beam impacts.

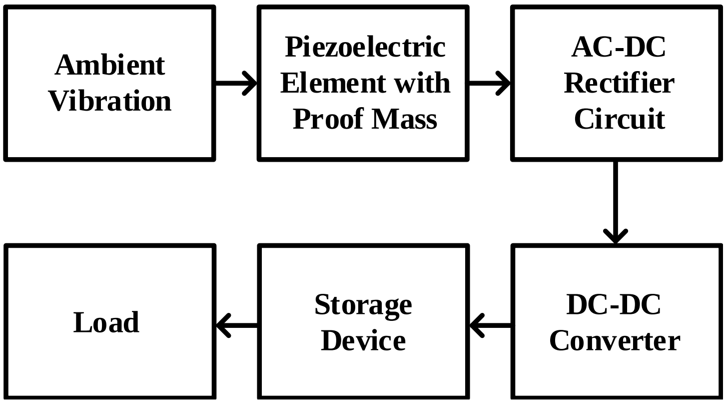



**Fig. 2.** Block diagram of energy harvesting from vibrations

However, in linear approach it is possible to use only resonance frequency or close to resonance frequency. In this work it has been tried to use nonlinear approach for using many frequencies to produce more voltage and consider good band of device in which band it can produce good voltage with good efficiency. The ambient source, transducer, and storage device for the piezoelectric energy harvester have been presented in block form (in Fig. 2). Static and dynamic validation modes are used to validate the model. The piezoelectric harvester has been tested in the lab using a shaker and in the field with various frequencies of walking. There are two types of experimental characteristics that have been observed. A load cell with various masses was utilised to transfer the beam between two states by adjusting the pre-compression to define the static mode.

The harvester has been made of two PZTs, a rectifier, a converter and a storage device. The used cantilever beam must be in the size of 10 $cm$ and 1 $cm$ by dimension on the other hand thickness must be 100 µm. The mechanical device can switch between its two stable states under the influence of vibrations of different frequencies. Two ultra-sensitive piezoelectric transducers have been used to

**Fig. 3.** Experimental Setup for the energy harvesting from vibration using piezoelectric materials

convert the beam impacts into electric charges. The beam has been switched freely with the help of clampers [9].

In Fig. 3 it has been shown a mechanical device consisting of two piezoelectric materials (V21BL), two clampers, one proof mass and one cantilever beam of plastic material.

## 4. Result and Discussion

A bi-stable structure has been developed in a piezoelectric harvester to get nonlinear snap-through phenomenon. Bi-stable structures enable a big geometric deformation using a small amount of trigger energy input to the system. Various researches have been conducted using the geometric nonlinearity of the snap-through effect to amplify actuation displacement. A piezoelectric material (PZT) has been used here to actively induce snap-through. The straight beam was initially pre-compressed by $2mm$, $3mm$, and $4mm$ to achieve output displacements of (17-16.5) $0.5mm$, (18-17) $1mm$ and (20-18) $2mm$ respectively. These pre-compressions values were chosen because they are small enough that they would not violate the small-deflection theory and to avoid plasticity setting in the beam during the experiment.

In Fig. 4, there is a relationship between pre-compression and bi-stable distance. It has been tried to see that beam switches after fixing the precompression and increasing the bistable distance.

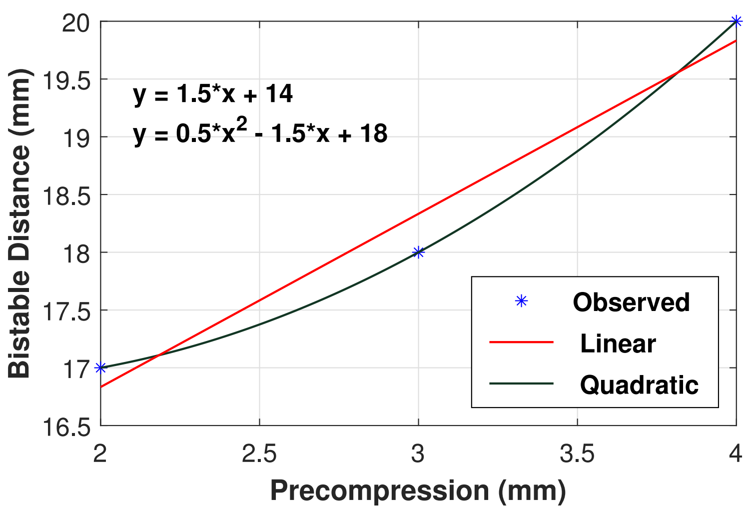



**Fig. 4.** Relationship between bistable distance and precompression

Vol. 2, No. 3, 2022, pp. 467-476

### 4.1. Statics Characteristics

On the basis of applications, this device could be used in different places for example in irrigation, in medical industry, in small scale electronics industry to charge small scale sensors or small chip. For this reason this energy harvester need to be fixed in those applicable areas where vibration might be low. The main advantage of this energy harvester is that it can generate energy with low reaction force in static mode which is shown in Fig. 5a.

Firstly equation (4) has been fitted to observe the behaviour of the reconstructed reaction force from experimental data. Using the force from load cell the beam has been stressed at the centre. Using load cell the applied force has reliably calculated. Until the beam switches between two stable states the beam deflection has been experimented. It has been shown the reaction force and displacement relationship for the case 4 mm pre-compression presented in Fig. 5a.

In static characterization it has been used three different mass to move beam and converted this mass into force which has been shown in equation (5), (6) and (7) for 2, 3 and 4 mm precompression. From this equation following Fig. 5b can be found [10].

For 2 mm precompression.

$$F_2 = \frac{9.8 \times 1.65}{1000} \tag{6}$$

For 3 mm precompression.

$$F_3 = \frac{9.8 \times 3.53}{1000} \tag{7}$$

For 4 mm precompression.

$$F_4 = \frac{9.8 \times 5.38}{1000} \tag{8}$$

In this paper it has been considered that the switching mechanism from various frequencies, i.e., author tried to observe the information according to energy barrier which means the external force must overcome the energy barrier to activate switching between the two stable states. In Fig. 5c, the kinship among the potential energy and displacement has been shown.

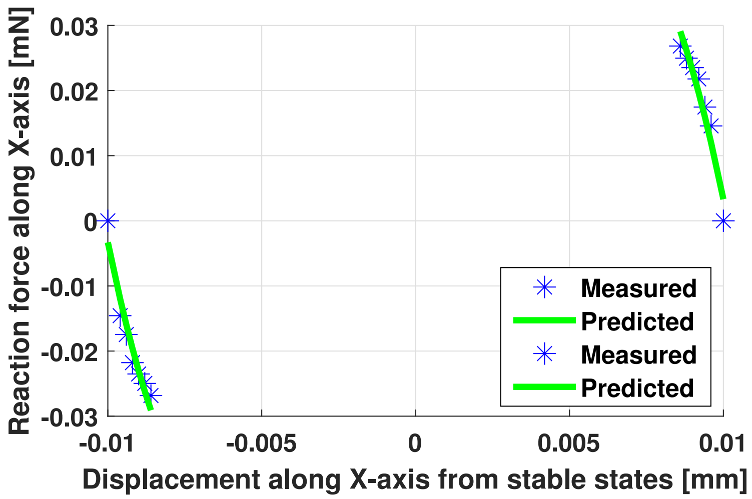
A bistable system has been simulated, showing two potential wells separated by a potential wall of magnitude $\Delta U$. The $x = 0$ position is now an unstable equilibrium, while $-Xs$ and $Xs$ two stable equilibria. Oscillation at the right side of '$0'$ positions represents intra-well oscillation, while left side of '$0'$ position illustrates inter-well hopping (snap-through state) when the energy input exceeds $\Delta U$.

### 4.2. Dynamic Characteristics

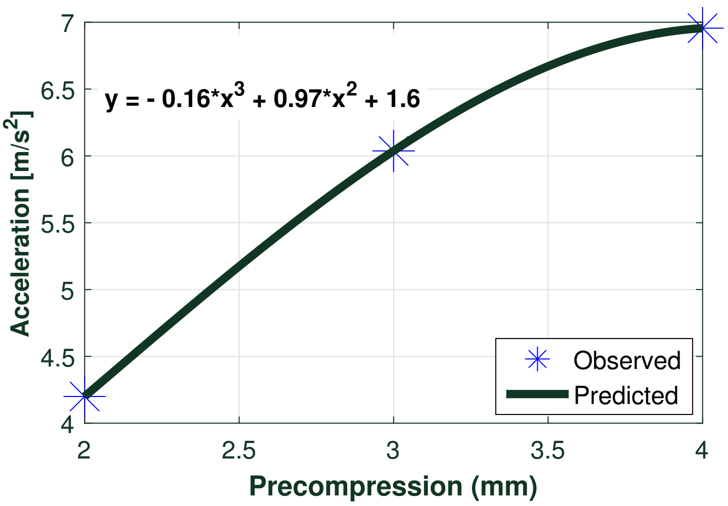
For Dynamical characterization it has been used here one accelerometer, one infrared sensor, shaker and wiring oscilloscope to gain data. Buffering has been used for transferring signal from piezoelectric material to oscilloscope. One axis of accelerometer has been used here because the beam of this device moves in one direction. Obviously, direction depends on how the device is placed. As all know nonlinear device can work in wide band of frequency so it has been used here 500 mHz and 1,2, 4,5,8,10,15 Hz acceleration frequency and observed the phenomena which is shown in Fig. 6a. It can clearly understand that after a certain frequency, the device does not work properly [10].

From Experimental work it has been demonstrated beam displacement, acceleration, and voltage from piezoelectric transducer by using shaker which is shown in Fig. 6b. In this experiment it has been shown that frequency of vibrations can be varied between 500 mHz and 15 Hz as well as amplitude of these frequencies has been changed perfectly. It has been observed that in frequency range of 500 mHz to 5 Hz the device works properly and gives good efficiency. As some voltage is found from experiments it needs to convert this voltage into displacement. Here an equation for this purpose has been written.

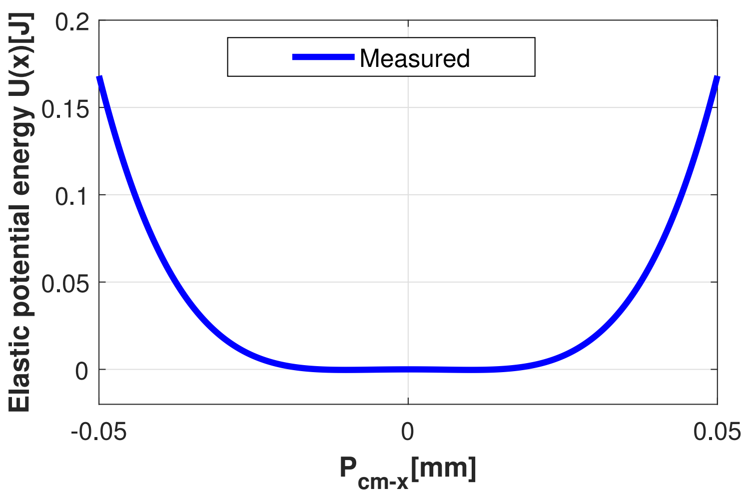
$$D = 0.266 \times I^2 - 2.15 \times I + 4.37 \tag{9}$$




(a)




(b)




(c)

**Fig. 5.** Relationship between: (a) displacement and reaction force, (b) acceleration and precompression, and (c) potential energy and displacement [$P_{cm-x}$: displacement of a central mass along x-axis from initial position ].

Vol. 2, No. 3, 2022, pp. 467-476

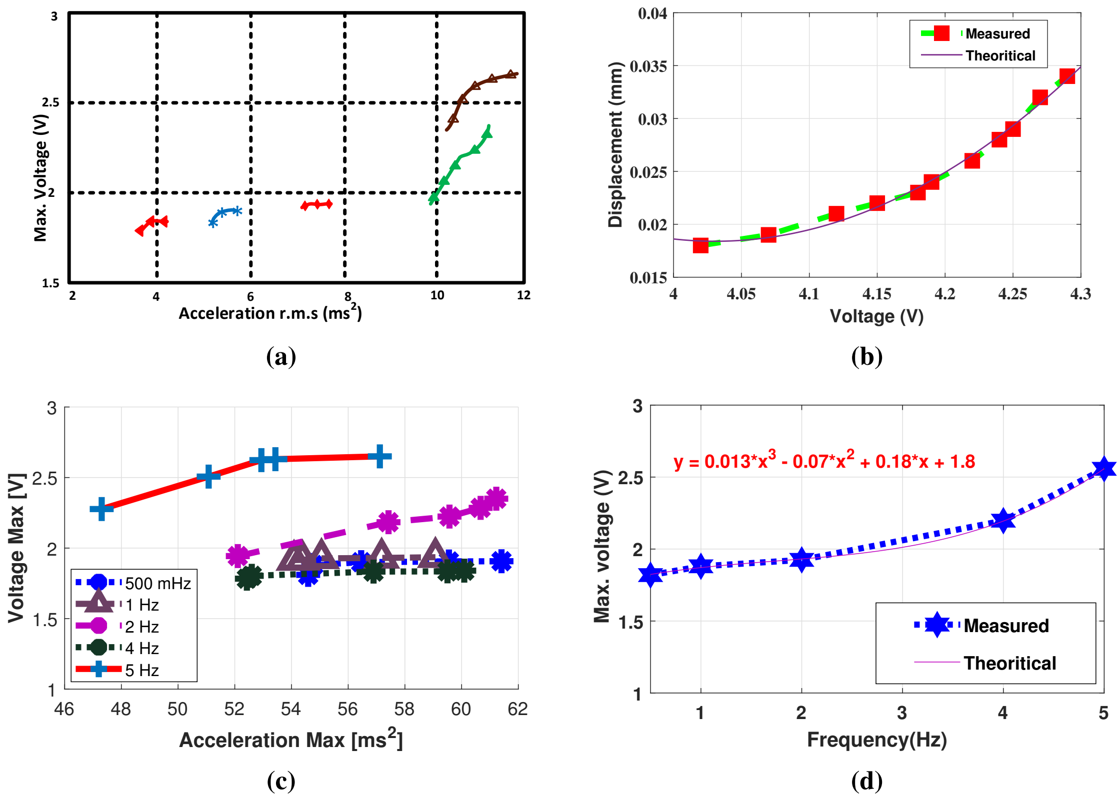



**Fig. 6.** Relationship between: (a) maximum voltage and acceleration, (b) voltage and displacement, (c) maximum voltage and maximum Acceleration, and (d) maximum voltage and frequency.

Where $D$ is the displacement, and $I$ is the voltage from Piezo transducer.

In both cases of Fig. 6c it has been shown that this piezoelectric harvester can overpass the cut-off value of 1.4 V and switch the electronics devices. It is observed that this mechanical device can generate voltage at minimum frequency of 0.5 Hz and if we increase the frequency of vibrations, the device can produce more voltage. This device shows good efficiency until 5 Hz but after 5 Hz it does not work properly. So, it can be said that the band of this device is 5 Hz with proper efficiency. This is the benefit of nonlinear system over linear one because of wide band. In linear case it is possible to use only resonance frequency or near to resonance frequency [11].

By increasing frequency it is also possible to increase voltage from piezoelectric harvester device which is presented in Fig. 6d. But due to bandwidth restriction of this device it is not possible to use higher frequency than 5 Hz. Output result shows the basic tool for understanding of dynamic systems. This result can be easily obtained by applying a sinusoidal vibration to the piezoelectric harvester and measuring its output voltage or power. From this study it can easily be said that, a linear system is very easy to investigate due to its response will be strong at the resonance frequency but it cannot work for various frequencies. On the other hand nonlinear system can scavenge energy from various frequencies of vibration. Finally it can be said that this piezoelectric harvester is crucial for future energy crisis from wide band vibration as it can generate maximum energy with minimum range of frequencies. This mechanical harvester also does not have any energy loss from the beam displacement and mechanical to electrical conversion. The main novelties of this paper are switching rate. The bi-stable beam switches very fast and can generate the voltage 1.7 volt through 500 mHz which is essential to switch electronics devices.

## 5. Conclusion

In this study, a nonlinear piezoelectric energy harvester was successfully developed. The key objective of this study was to develop a mechanical device that could scavenge energy from diverse vibration frequencies. Two types of experiments were carried out, and it was found that the device's generated energy can exceed the 1.4 volt threshold, which is sufficient for charging capacitors in electronics devices. Compared to electromagnetic harvester, piezoelectric harvester can produce high voltage and low current. A variety of measures have been conducted applying vibration of various frequencies to improve the vibrational response and thereby improve the energy harvesting efficiency. This mechanical device has been shown to have a high efficiency in the frequency range of 500 mHz to 5 Hz. Since this device operates over a wide range of vibration frequencies, it uses a nonlinear mechanism rather than a linear one, which can only scavenge energy at a resonant frequency of oscillation. The energy harvested could be stored or fed into a grid for future generation.

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