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Wideband Non-linear Vibration Piezoelectric Energy Harvesting Using a Piecewise-linear Mechanism

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ABSTRACT

In recent years, energy harvesting technology has been given a lot of attention due to its capability to produce clean and sustainable energy to power electronic devices. The applications of this technology involve the area of biomedical, automotive, industrial, and even military applications. Currently, the energy harvesting device is made for more than one purpose. Due to similar operating characteristics, apart from tapping the ambient energy, it is also used as the dynamic vibration absorber (DVA). However, the conventional linear mechanism adopted in the system is limited to only in a restricted bandwidth. This paper proposes a newly designed non-linear piezoelectric energy harvesting device which was also adopted as a non-linear DVA (NDVA) by using a piecewise-linear stiffness mechanism. The mechanism consists of a cantilever beam constrained by two limit stoppers, which are adjustable in both horizontal and vertical directions. The restoring force-deflection behaviour for different limit block configurations was characterised using quasi-static measurement. The dynamic study was conducted for different limit block configurations and input amplitudes. The study on the dynamic behaviour shows that the device can widen the harvesting frequency bandwidth compared to its equivalent linear DVA.

Keywords: Non-Linear Vibration Absorber, Piezoelectric Energy Harvesting, Piecewise-Linear Stiffness.

1. INTRODUCTION

Energy harvesting can be characterised as a technique that permits capturing the freely available energy in nature and changing it into electrical energy that can be utilised or stored. Harvesting energy is one of the most encouraging techniques in global energy issues. The energy can be obtained from many different sources such as ambient light, wind, heat, strain, and vibrations. However, throughout recent years, particular attention is given to harvesting energy from the low-frequency vibration sources, especially when involving micro-power applications [1]. It is due to its simplicity to install, lightweight and has an unlimited lifespan.

There are three main approaches to convert vibration energy into electrical energy which are electromagnetic [2-6], electrostatic [7,8], and piezoelectric material [9-12]. Electromagnetic principles deal with electricity and magnetism which generates energy from the current produced in the coil due to the relative motion between the magnet and the coil. It is depending

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on the strength of the magnetic field, the frequency of motion between magnet-coil and the number of turns, or the area of the winding wire. As for the electrostatics, the relative movement between two dielectrically insulated electrodes (capacitor) is exploited. Plates are charged by periodic contact to the source of the voltage or using electrets. The energy of the electrostatic potential is retained in the capacitors. The harvested energy is gained from the work done between the plates against the electrostatic force. While piezoelectric is a smart material that produces electrical energy when subjected to mechanical stress (pressure) or strain (deformation). Piezoelectric materials are available in many types, such as single crystal (quartz), piezoceramic (lead zirconate titanate or PZT), thin-film, and polymeric materials (polyvinylidene fluoride or PVF) [13]. The piezoelectric material method was chosen for this study due to simplicity, which can be easily integrated into the system and its low cost [14].

The advancement of this technology has seen many potentials in military and defence applications. Intense studies have been conducted, for example, in wireless sensor networks (WSNs) [15-17], Radio-frequency Identification (RFID) [18], Internet of things (IoT) [19] and Condition Based Maintenance (CBM) system [20]. One of the examples of the military application utilising the technology is the recent development of energy harvesting backpack for a soldier [21]. Soldier backpacks used in fieldwork contained many electronic devices that required high power consumption and uninterrupted power to carry out their mission. Since they were also used for a long period, the battery carried by the soldier tends to be bulky and heavy. This invention extracts energy using the biomechanical vibration energy during walking or running to power the electronic devices sustainably.

However, most vibration-based energy harvesters are built as linear resonators which only operate efficiently near their resonant frequencies with limited bandwidth [22]. In this case, to optimally harvest the energy, the harvester needs to be designed such that its natural frequency matches the source frequency. Unfortunately, in most realistic cases, the frequency of the ambient vibration sources spread over a wide range [23]. Thus, if a linear generator is to be used, it needs a constant adjustment of its natural frequency to match the ambient frequency in order to operate at its optimum level. Therefore, having a vibration energy harvester which can operate in a wide frequency range has become one of the key research areas before these harvesters can be widely used in practice. Nowadays, the purpose of the energy harvester is not only to tap the ambient energy. It is also used as a dynamic vibration absorber (DVA) to suppress the troublesome vibration. The needs for good vibration absorption property make it even more critical for the energy harvester to operate effectively within the targeted frequency range.

One of the ways to realise a wide frequency range energy harvester is by employing a non-linear vibration-based energy harvester. Among many of the non-linear mechanisms approached by researchers up to now, the non-linear stiffness mechanism emerges as one of the most practical ones. Several non-linear stiffness mechanisms have been proposed by researchers to enhance the bandwidth of an energy harvesting device. One of them is by employing a non-linear hardening stiffness in the mechanism. The non-linear hardening stiffness skews the frequency response curve towards the higher frequency at a much slower rate with respect to the excitation frequency, thus increasing the half-power bandwidth of the response. Commonly, the hardening stiffness is incorporated into the energy harvesting mechanism using the magnetic stiffness [24,25]. However, magnetic stiffness tends to change the characteristics of the device's linear natural frequency as the degree of the non-linearity changes. This limits the capability of the device to target the ambient frequency of interest effectively.

This can be resolved by utilising the piecewise-linear stiffness mechanism which provides a more controllable way of obtaining higher frequency bandwidth [26,27]. The mechanism consists of a stopper to limit the motion of the cantilever beam and seismic mass of the existing linear generator. The presence of the stopper hardens the stiffness of the system. It produces not only a similar dynamic characteristic to the one with the hardening stiffness but even better with the inclusion of the sturdy tuning mechanism [28]. However, the static properties and the power generation of the non-linear piecewise-linear stiffness mechanism have only be studied in terms of the vertical gap between the beam and the single stopper. This paper presents a newly designed non-linear energy harvester capable of increasing the operating bandwidth, using the piecewise-linear mechanism. This paper also extends the study by introducing a mechanism that can vary the vertical gap and the horizontal position of the stopper. Besides, this paper also presents a parametric study on the effect of the vertical gap and the horizontal position of the stopper to the static and dynamic properties of the energy harvesting device. The static property focuses on the experimental characterisation of the force-deflection relation. The dynamic property investigates the performance of the proposed mechanism in terms of the frequency bandwidth of energy generated compared with the linear one.

2. METHODOLOGY

2.1 Device Mechanism Development

The non-linear energy harvesting device was realised using a piecewise-linear stiffness mechanism instead of a conventional linear stiffness. It consists of a fixed-free cantilevered beam constrained by two stoppers with a tip mass attached at the free end. The linear stiffness of the system, k_1 is given by:

$$k_1 = \frac{3EI}{L^3} \tag{1}$$

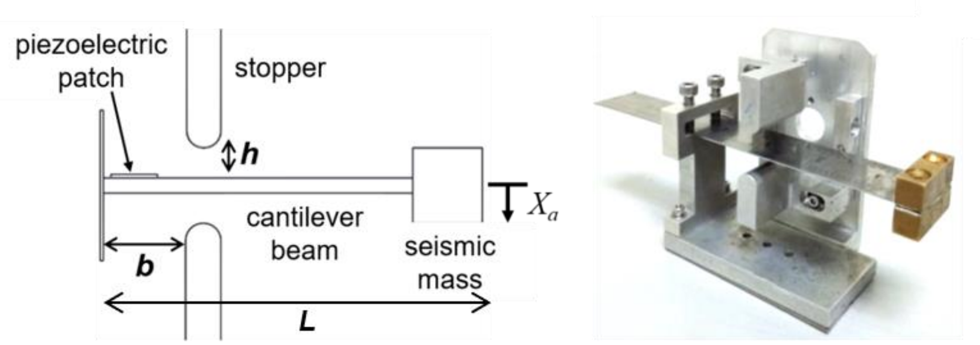
where E is the modulus of elasticity, I is the second moment of area and L is the effective length of the beam. The mechanical properties of the cantilever beam are tabulated in Table 1. The linear natural frequency of the system, $\omega_n = k_1/m$ is tuned by changing the stiffness of the cantilever beam. Most often, this is done by adjusting the effective length of the beam. The limit blocks are designed such that their vertical gap, h, and horizontal position, b are adjustable. The adjustable block can alter its vertical gap, h from the equilibrium position of the beam using the rack and pinion gear mechanism. The rack and pinion system ensures an identical vertical gap for both top and bottom adjustable blocks from the equilibrium position of the beam. The maximum gap between the block and the beam that can be achieved is 5 mm. As for the horizontal position, b, the block can be moved horizontally to provide different constrained locations from the fixed end of the beam. For this mechanism, the range of the horizontal gap that can be adjusted from the fixed end of the beam is from 25 mm up to 50 mm. The constrained motion because of the inclusion of the limit blocks produces non-linear stiffness in the form of piecewise-linear stiffness, which has almost similar characteristics as the hardening stiffness. The resulting restoring force, F can now be represented as:

$$F = k_1 x_a + k_3 {x_a}^3 \tag{2}$$

where k_3 is the non-linear stiffness resulting from the constrained motion of the beam because of varying of the vertical gap and the horizontal position. When the response is small, the system vibrates under the influence of the linear stiffness, k_1. This is termed as the unconstrained region's stiffness. When the motion of the beam is constrained by the stoppers, the system vibrates dominantly with the non-linear stiffness which is termed as constrained region's stiffness. The FS-2513P piezoelectric patch was used as the energy generation element piezoelectric patch attached on the beam, as shown in Figure 1 and its specifications are as listed in Table 1.

Table 1 Piezoelectric patch specifications and mechanical properties of the cantilever beam

		Specification	Unit
Piezoelectric patch	Model Number	FS-2513P	-
	Type	PVF	-
	Dimension	20 x 25	mm
	Capacitance	1.5 ± 30%	ηF
	Internal Resistance	1.5	MΩ
Cantilever beam	Young's Modulus, E	1.60×10^{11}	N/m^2
	Thickness of Beam, t	0.75	mm
	Length, L	120	mm
	Breadth, b	26	mm
Tip mass	Mass, m	40	gram



(a) (b)

Figure 1. (a) Schematic and (b) photo of a non-linear energy harvester.

2.2 Characterization Using Quasi-Static Measurement

The piecewise-linear stiffness behaviour was characterised by using a quasi-static measurement approach to evaluate the relationship between the restoring force, F against tip deflection, X_a. The measurement was done by exciting the base of the non-linear energy harvesting device at a low frequency of 0.75 Hz. The restoring force due to the resulting deflection tip was measured using a load cell. Meanwhile, the displacement of the base of the energy harvester was measured using the laser triangular sensor. The measurement was conducted for different vertical gaps and horizontal positions. Similar configurations were also used when investigating the dynamic behaviour of the proposed non-linear energy harvesting device.

2.3 Performance of Non-linear Piecewise-linear Stiffness Energy Harvester

First, the open-circuit voltage of the linear energy harvesting device was measured across the sweep frequency range. The natural frequency of the linear and the non-linear energy harvesting devices were both fixed at 19.5 Hz. For the non-linear energy harvesting device, the open-circuit voltage was measured for different limit block configuration of horizontal position, b i.e. 35 mm, 40 mm and 45 mm and vertical gap, h i.e. 1 mm, 2 mm, and 3 mm. The effect of different input displacement amplitude, X_b i.e. 0.3 mm, 0.4 mm and 0.5 mm was also measured. The setup for the experiment is illustrated in Figure 2.

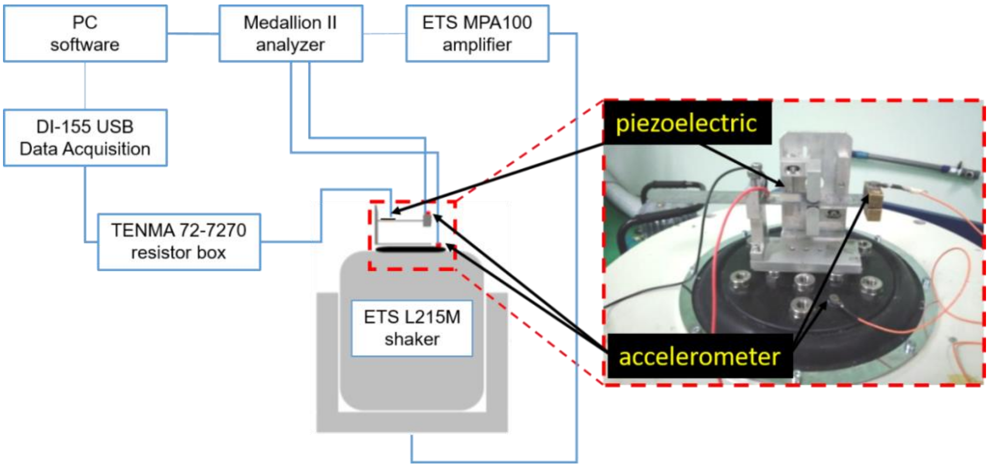


Figure 2. Experimental setup for dynamic measurement.

The experiment was conducted by exciting the base of the harvesting device which is attached to the ETS L215M electrodynamic shaker. The excitation signal of the shaker was generated by the VR Medallion II shaker controller through the ETS MPA100 power amplifier. The non-linear energy harvesting device was excited harmonically by increasing the frequency (sweep-up) from 10 Hz to 40 Hz and followed by the decrease in frequency (sweep-down) from 40 Hz to 10 Hz at a sweep rate of 0.5 Hz/sec. The Dytran 1051V1 accelerometers measured the response at the tip mass and the feedback amplitude of the shaker. As for the generated voltage, the response was measured using the DATAQ Instrument DI-155 USB data acquisition kit. The results obtained in the form of voltage generated for different limit block configuration and input displacement amplitude were presented accordingly. The performance of the non-linear energy harvesting device was reported in terms of the useful frequency bandwidth and this was determined by using the half-power bandwidth method [29].

2.4 Power Generation by Resistive Load

For the closed-circuit measurement, the same setup was used as in the open-circuit measurement but with an inclusion of the resistive load shown in Figure 2 at a fixed value of 1.5 MΩ (internal resistance of piezoelectric component). The system will generate the largest output power when the load resistance is equal to the internal resistance of the piezoelectric element [7]. The voltage produced by the device was then recorded, and the averaged output power generated, and half-power bandwidth was calculated and compared against the output power by linear energy harvesting device. However, it is worth to note here that the main purpose of the study is rather to see the increase in the frequency bandwidth as a result of using a piecewise-linear stiffness mechanism rather than the maximum power.

3. RESULT AND DISCUSSION

3.1 Characterisation of the Static Behaviour

Figure 3 and 4 show the measured force-deflection relationship for different horizontal position, *b* and vertical gap, *h* configurations, respectively. The measured data show that the piecewise-linear restoring force characteristics have two different stiffness regions namely low-stiffness region (unconstrained region) and high-stiffness region (constrained region). From both Figure 3 and 4, the increase in the horizontal position, *b* increases the constrained region and vice versa. It is also noticed that the curve for the different vertical gap, *h* configurations produce almost a similar constrained region gradient. This shows that the hardened stiffness in the constrained region is highly dependent upon the horizontal position, *b* rather than the vertical gap, *h*. However, the vertical gap, *h* controls the maximum response of the tip mass. Another useful feature of the mechanism is the fixed linear stiffness (unconstrained region's stiffness) under a various degree of the non-linearity i.e. various configurations of the vertical gap and horizontal position. This feature is absent in the existing non-linear mechanism utilizing magnetic stiffness. The fixed linear stiffness offers a huge advantage when targeting a specific range of ambient frequency.

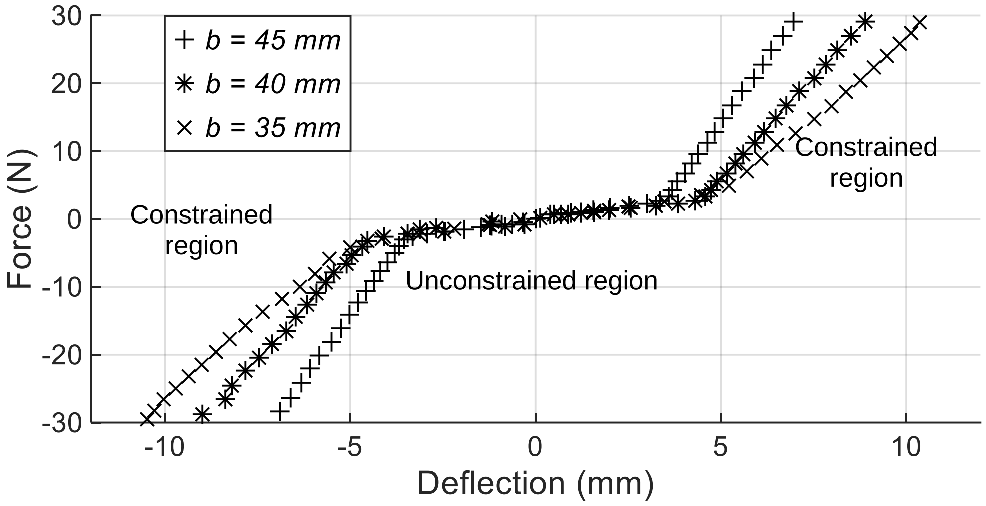


Figure 3. The measured force-deflection curve for different horizontal positions, *b* at *h* = 1 mm.

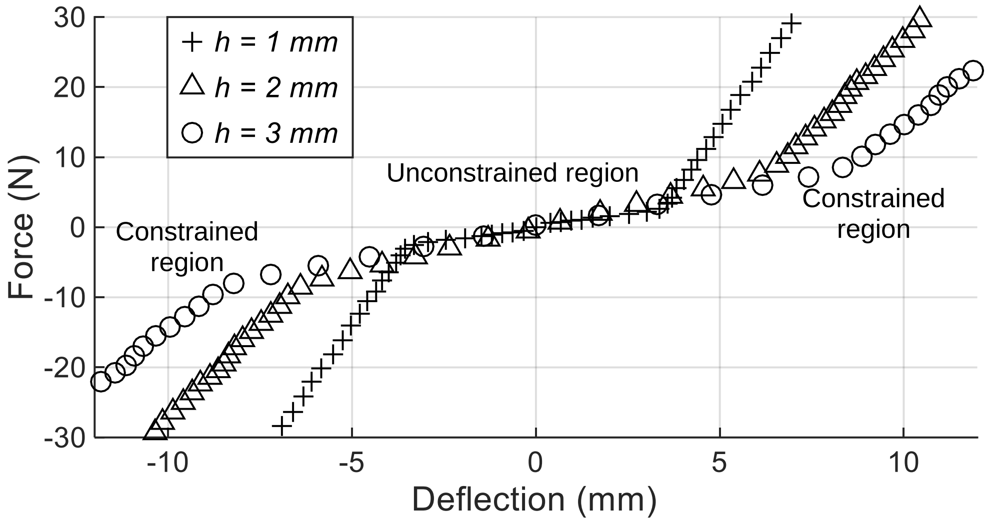


Figure 4. The measured force-deflection curve for the different vertical gap, *h* at *b* = 45 mm.

3.2 Open-Circuit Voltage Generation

Figure 5 shows the measured voltage produced by the linear mechanism where a single maximum voltage of 1.4 V was generated at the natural frequency of the device of 19.5 Hz. The non-linear system requires a certain amplitude of excitation to initiate the contact between the beam and the stopper in order to produce a non-linear response in the form similar to the well-known hardening Duffing oscillator. Once contacted, the frequency response function bends towards the higher frequency during frequency sweep-up until jump-down phenomena occur which increases the half-power bandwidth of the response. As this energy harvesting mechanism is used as part of the dynamic vibration absorber application, only the forward sweep frequency response is considered because it is much more significant than the backward sweep response due to its larger response. Figure 6 and 7 show the measured voltage against the excitation frequency for different horizontal position, *b* and vertical gap, *h,* respectively. They show that the limit block configuration highly determines the characteristic of the piecewise-linear stiffness. The larger the horizontal position, *b,* and the smaller the vertical gap, *h*, respectively, produce much wider frequency bandwidth. Table 2 summarises the comparison of the performance of the linear and the non-linear energy harvesting device of different stopper configurations in terms of the half-power bandwidth.

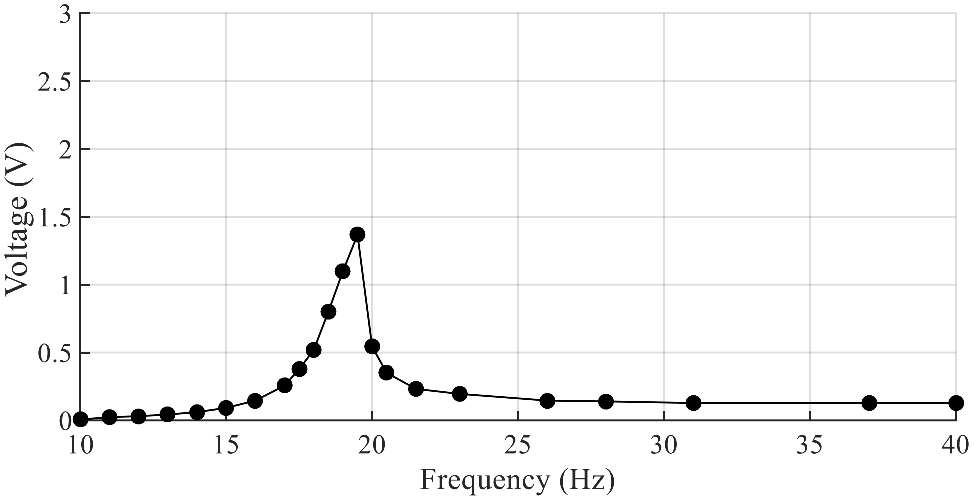


Figure 5. Measured voltage against frequency for the open-circuit linear system.

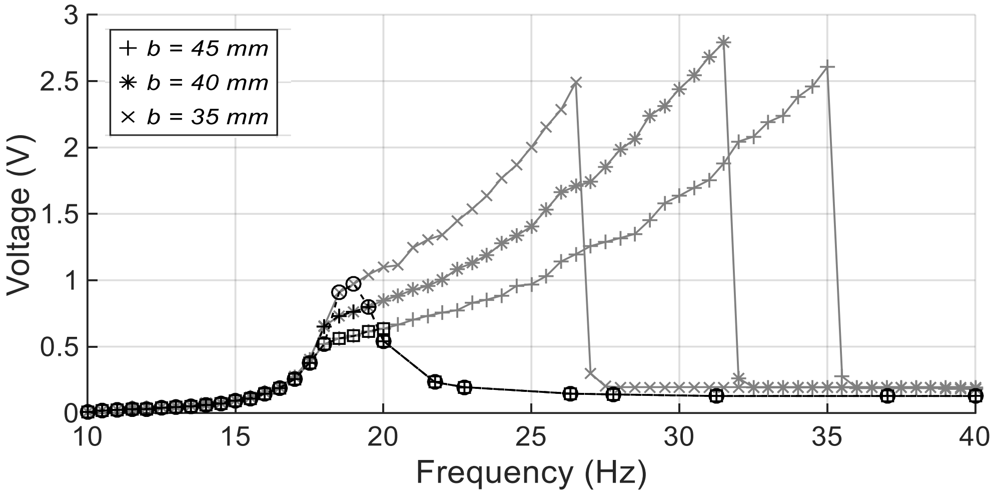


Figure 6. Measured voltage against frequency for the open-circuit non-linear system for different horizontal position, *b* at *h* = 1 mm.

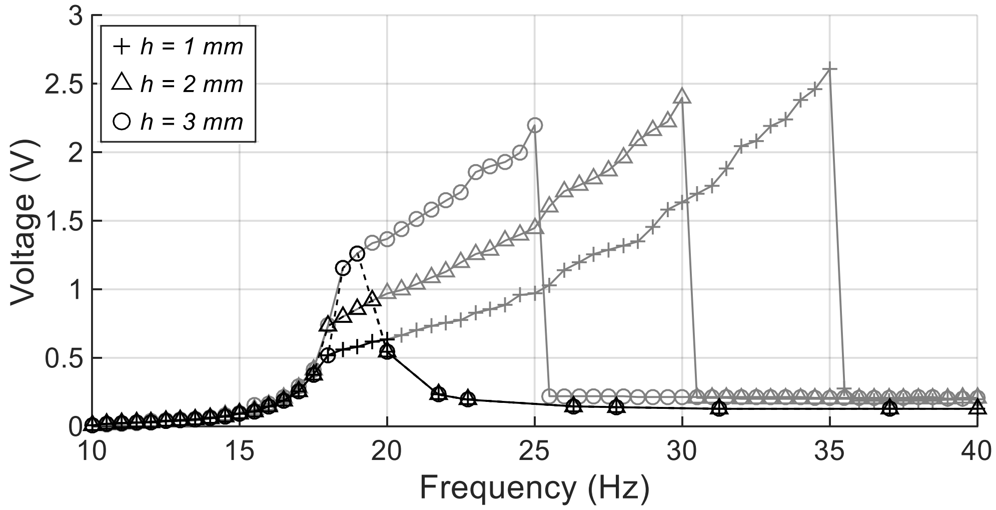


Figure 7. Measured voltage against frequency for the open-circuit non-linear system for the different vertical gap, h at b = 45 mm.

The dependence of the dynamic response on the input displacement amplitude was also investigated. For a non-linear system, at a low excitation level, the frequency response behaves similar to the linear system. The non-linear system requires a certain amplitude of excitation to initiate the contact between the beam and the limit block in order to produce a non-linear response. Once it happened, the response bends the frequency response towards the higher frequency during frequency sweep-up until jump-down phenomena occur. As for the jump-up phenomenon, it shows a less significant response to this kind of mechanism. Figure 8 shows the effect of different input displacement, X_b of 0.6 mm, 0.8 mm, and 1.0 mm. The result shows that the larger input displacement of the same configuration produces higher frequency bandwidth. The large input drives the system more into the constrained region's stiffness, thus skewing the frequency response curve even more to the high frequency.

Table 2 Measured half-power bandwidth of the open-circuit linear and non-linear energy harvesting device with different configurations

Horizontal position, *b* (mm)	Vertical gap, *h* (mm)	Jump-down frequency (Hz)	Jump-up frequency (Hz)	Half-power bandwidth (Hz)
Linear device		-	-	0.8
35	**1**	26.5	19.5	3.5
40		31.9	19.7	3.9
45		35.1	20.2	4.1
45	**2**	30.0	19.6	3.8
45	**3**	24.9	19.5	3.4

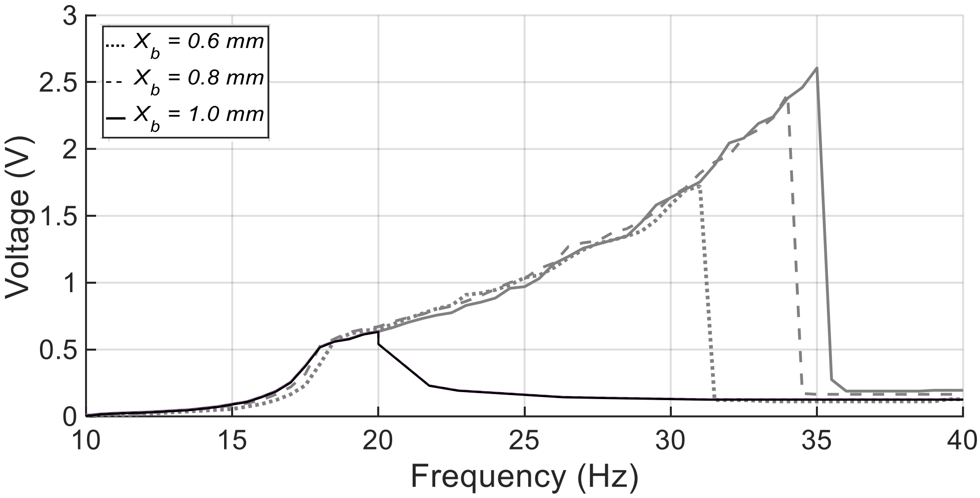


Figure 8. Measured voltage against frequency for the open-circuit non-linear system for different input displacement amplitude, X_b.

3.3 Power Generation by a Resistive Load

In the case of a linear DVA harvesting device, the maximum power generated obtained was 1.25 µW as shown in Figure 9. Figure 10 shows the measured power against the excitation frequency for the closed-circuit non-linear system. The stopper was set at three different horizontal positions, *b* of 35 mm, 40 mm, and 45 mm under the same vertical gap, *h* of 1 mm while the amplitude of the base displacement was fixed at 1 mm. The maximum power was obtained at the horizontal position of the limit block, *b* at 40 mm. An increase in the horizontal position of the limit block increases the frequency bandwidth because the beam was constrained earlier compared to the smaller horizontal position, thus causing it to have greater constrained stiffness. Table 3 summarises the comparison of the performance of the linear and the non-linear energy harvesting device of different stopper configuration.

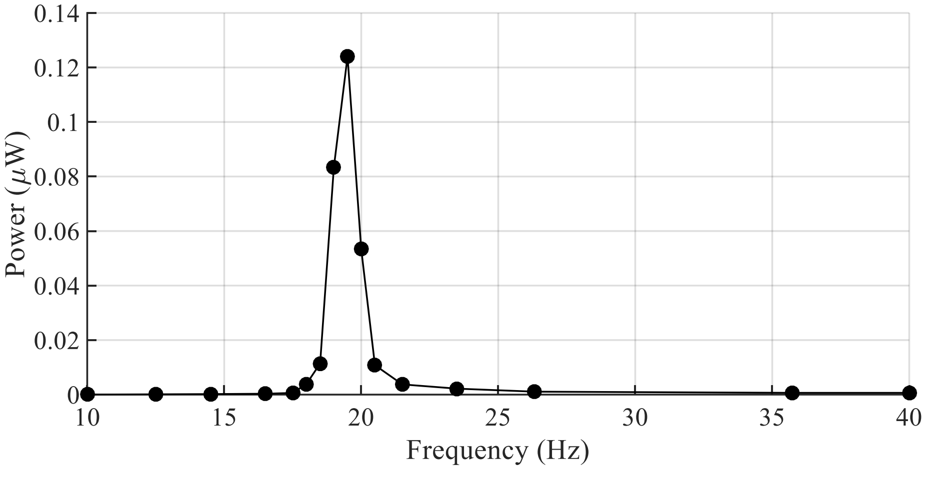


Figure 9. Measured power against frequency for the closed-circuit linear system.

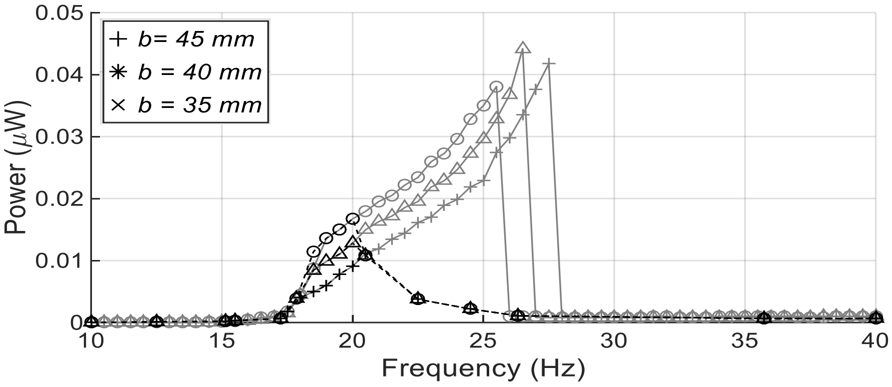


Figure 10. Measured power against frequency for the closed-circuit non-linear system for different horizontal position, b at h = 1 mm.

Figure 11 shows the power generated in the load resistance against the frequency when the vertical gap of the limit block was set at 1 mm, 2 mm, and 3 mm while the horizontal position, b was maintained at 45 mm. It shows that when the vertical gap of the limit block decreases, the maximum output voltage increases. The reason for this is, when the vertical gap, h decreases, the smaller gap between the beam and the limit block causes the constrained stiffness to be higher. This extends the maximum response to a much higher frequency, thus resulting in a larger amount of power generated. Most importantly, the half-power bandwidth of the device increases with the decrease in the vertical gap.

The comparison in terms of the maximum power generation between the linear and non-linear harvesting devices is not even valid since they occurred at different frequencies. The comparison can be made valid by adjusting the non-linear harvesting device's parameter so that the maximum response occurs at the same frequency as the linear one. However, that is the story that this paper is trying to highlight. If the ambient frequency is fixed, then the linear device is the most suitable device to tap the energy. However, when the ambient sources have a varying frequency, the linear device may not be an effective method to tap the energy. In this case, the piecewise-linear stiffness mechanism may outshine the linear device in terms of tapping a fair amount of energy for a wider frequency range. That is, of course, valid when the power generated by the piecewise-linear stiffness produces enough power for the targeted applications.

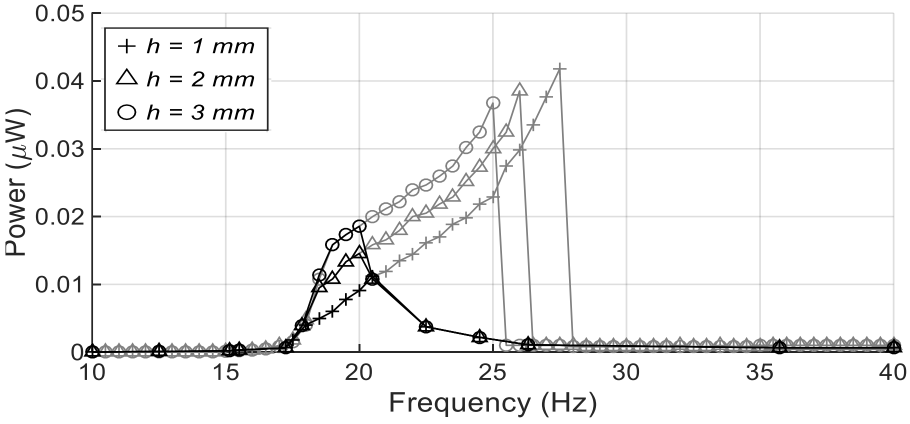


Figure 11. Measured power against frequency for the closed-circuit non-linear system for the different vertical gap, h at b = 45 mm.

Table 3 Measured half-power bandwidth of the closed-circuit linear and non-linear energy harvesting device with different configurations

Horizontal position, *b* (mm)	Vertical gap, *h* (mm)	Jump-down frequency (Hz)	Jump-up frequency (Hz)	Half-power bandwidth (Hz)
Linear device		-	-	0.8
35	**1**	25.8	19.8	1.3
40		26.5	20.0	1.5
45		27.5	20.2	1.7
45	**2**	26.0	19.9	1.4
45	**3**	25.0	19.8	1.2

Figure 12 shows the effect of power generated from different input amplitudes. The increase in the input amplitude drives the response further into the constrained region as shown in Figure 3 and Figure 4. This hardens the overall stiffness of the system. As a result, the largest input amplitude bends the frequency response furthest to the right, thus resulting in the broadest frequency bandwidth.

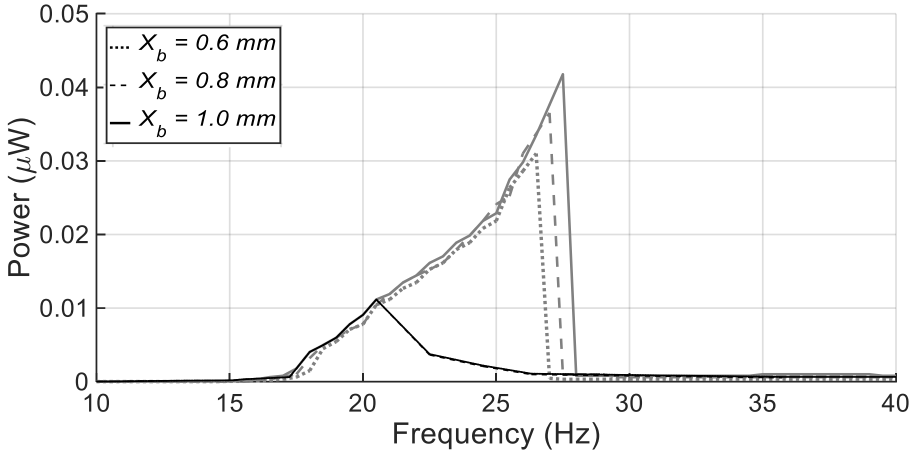


Figure 12. Measured power against frequency for the closed-circuit non-linear system for different input displacement amplitude, X_b.

4. CONCLUSION

This paper proposed the implementation of a non-linear energy harvesting device which may also act as a non-linear dynamic vibration absorber. The non-linearity of the system is generated by the piecewise-linear stiffness mechanism. The mechanism is realized by adding a stopper on either side of the cantilever of the commonly used linear energy harvester mechanism. The proposed mechanism offers a unique tuning advantage over the existing magnetic non-linear stiffness mechanism. The non-linear energy harvesting device has proven to widen the frequency bandwidth, thus increasing the tolerance toward mistuning. In general, the device can produce 2.1 times the half-power bandwidth compared to the linear one. Unlike all the drawbacks of the existing non-linear hardening mechanism which uses magnetic stiffness, the linear natural frequency of the proposed non-linear mechanism does not change very much with the change in the horizontal position, *b* and the vertical gap, *h*. The almost “fixed” linear natural frequency makes it easier to target the ambient frequency of interest. The bandwidth around the targeted frequency can be increased or decreased by adjusting the horizontal position, *b* and the vertical gap, *h*. The bandwidth also increases with the increase in the excitation level.

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