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A review on performance enhancement techniques for ambient vibration energy harvesters

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Abstract

Due to increased demands for energy and the current limitations of batteries, a future prospective technology are vibration energy harvesters that convert kinetic vibration energy into electrical energy. These energy harvesters have the potential to be used in powering small electronic devices such as measurement equipment in remote or hostile environments where batteries are not a viable option. Current limitations of vibration based energy harvesters is the total available power generated and the frequency at which they effectively collect ambient vibration sources for producing power; this paper aims to review the current techniques that are being employed to enhance the performance of these devices. These techniques have been categorised into amplification techniques, resonance tuning methods and introducing nonlinear oscillations. Before this technology can be used effectively in applications enhancing the performance of ambient vibration energy harvesters needs to be addressed.

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A Review on Performance Enhancement Techniques for Ambient Vibration Energy Harvesters

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Abstract

Due to increased demands for energy and the current limitations of batteries, a future prospective technology are vibration energy harvesters that convert kinetic vibration energy into electrical energy. These energy harvesters have the potential to be used in powering small electronic devices such as measurement equipment in remote or hostile environments where batteries are not a viable option. Current limitations of vibration based energy harvesters is the total available power generated and the frequency at which they effectively collect ambient vibration sources for producing power; this paper aims to review the current techniques that are being employed to enhance the performance of these devices. These techniques have been categorised into amplification techniques, resonance tuning methods and introducing nonlinear oscillations. Before this technology can be used effectively in applications enhancing the performance of ambient vibration energy harvesters needs to be addressed.

Keywords

Vibration energy harvester, energy scavenging and performance enhancement, review, resonance tuning, nonlinear

1 INTRODUCTION

With increasing growth and population around the world, the demand for energy has become increasingly significant as living standards rise. Powering conventional small scale electronic devices is usually done through batteries however the technological increase of batteries over the last 2 decades has been relatively small compared to other computing hardware. This issue has led to the increased urgency of looking at alternative sources particularly in mobile and embedded systems [1]. There are also environmental concerns when disposing used batteries after operation.

With technological advancements in energy conversion from sources such as solar [2], wind [3], biomass [4] and vibration energy harvesting [5]; recent research into powering small electronic devices has emerged in particular with the design of vibration based energy harvester's (VBEH). Since ambient vibration sources are prevalent in many everyday applications making it a suitable power source for small electronic devices. These vibration sources exist in many systems such as industrial machinery, civil structures, cars, ship hulls and wireless platforms.

Vibration energy harvesting devices have the ability to convert ambient vibration energy from the surrounding environment into electrical power. The conversion of this kinetic energy is based on the relative displacement between the (VBEH) device and the structure it is attached to, this normally unwanted vibration can effectively be used to self-power sensors and other monitoring equipment in structures and machinery without the need for external power sources particularly in remote or hostile applications.

However issues concerning conventional vibration energy harvesters are they only operate in the vicinity of their resonance which impacts the effective operating range for a (VBEH) device to harvest electrical power. The overall power that can be scavenged is also limited dependent on the design of the device and the source vibrations amplitude and frequency. This means that even if the ambient vibration source is well documented and the source frequency is known the device needs to be manufactured precisely as small deviations will lead to significant power reductions.

Due to the issues of maximising the power output and the effective operating region of vibration based energy harvesting devices, this article presents a review on the performance enhancement techniques that are currently being utilised to address these key issues facing (VBEH) devices; these include power amplification, resonance tuning methods and the introduction of nonlinear oscillations. This paper presents the fundamentals of vibration based energy harvesting for completeness. A summary and comparison of the different methods based on the advantages and disadvantages will also be discussed for the applicability of each method.

2 FUNDAMENTALS OF VIBRATION ENERGY HARVESTING

Vibration energy harvesting theory is based on the relative displacement between a mass and the base excitation of a structure which is represented in Figure 1.

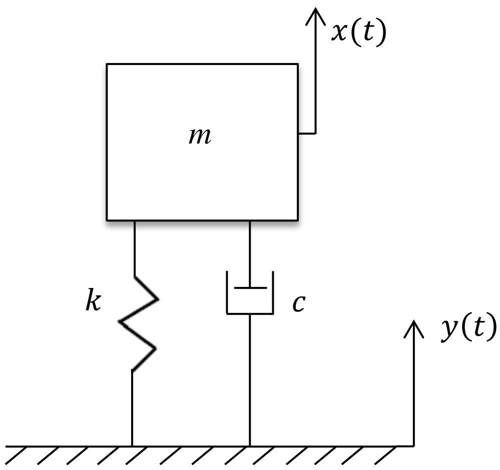

Figure 1: Single degree of freedom vibration energy harvester with base excitation

The governing equation of motion of this system is

$$m\ddot{z} + c\dot{z} + kz = -m\ddot{y} \tag{1}$$

where m is the mass of the system, $z = x - y$; the relative displacement between the mass and the base, $c = c_e + c_m$ is the damping coefficient comprising of both electrical and mechanical contributions and k is the device stiffness. Dividing through by the mass Eq. (1) can be rewritten in the form

$$\ddot{z} + 2\zeta\omega_n\dot{z} + \omega_n^2 z = -\ddot{y} \tag{2}$$

Where $\zeta = \frac{c}{2\sqrt{mk}}$ the total damping ratio of the system and $\omega_n = \sqrt{\frac{k}{m}}$ (rad s^{-1}).

The Laplace transform of Eq. (2) results in the system transfer function given by $H(s)$:

$$H(s) = \frac{Z(s)}{Y(s)} = -\frac{s^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \tag{3}$$

The response of this system under sinusoidal vibration can be modelled by applying $y(t) = Ycos(\omega t)$; where Y is the amplitude of the vibration and ω is the frequency of the vibration. The new governing motion of equation is:

$$\ddot{z} + 2\zeta\omega_n(\dot{z}) + \omega_n^2(z) = \omega^2 Ycos(\omega t) \tag{4}$$

The transfer function of Eq. (4) with $s = j\omega$ can be rewritten as:

$$H(j\omega) = \frac{Z(j\omega)}{Y} = \frac{\omega^2}{(\omega_n^2 - \omega^2 + 2j\zeta\omega_n\omega)} \tag{5}$$

The modulus and phase angle of the frequency response respectively are given by:

$$|Z(\omega)| = \frac{Y\omega^2}{\sqrt{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}} \tag{6}$$

$$\phi = \tan^{-1}(\frac{2\zeta\omega_n\omega}{\omega^2 - \omega_n^2}) \tag{7}$$

This system has a well-known steady state solution in the form of:

$$z(t) = \frac{Y\omega^2}{\sqrt{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}} \cos(\omega t - \phi) \tag{8}$$

The power that can be harvested is proportional to the force F and velocity v

$$P = \int_0^v F dv \tag{9}$$

This is the product of the damping force from (Eq. 1) and the velocity of the mass; this is given in Eq. (10)

$$P = \int_0^{\dot{z}} c_e \dot{z} d\dot{z} = \frac{c_e|\dot{z}|^2}{2} \tag{10}$$

Where $\dot{z}$ is the derivative of Eq. (8) given by:

$$|\dot{z}| = \frac{Y\omega^3}{\sqrt{(\omega_n^2 - \omega^2) + (2\zeta\omega_n\omega)^2}} \tag{11}$$

Substituting Eq. (11) into Eq. (10) the average power that can be generated in a vibration energy harvesting device in dimensionless form is derived as:

$$P_{dim} = \frac{P}{m\omega^3 Y^2} = \frac{\zeta_e \left(\frac{\omega}{\omega_n}\right)^3}{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega_n}\right)^2} \quad (12)$$

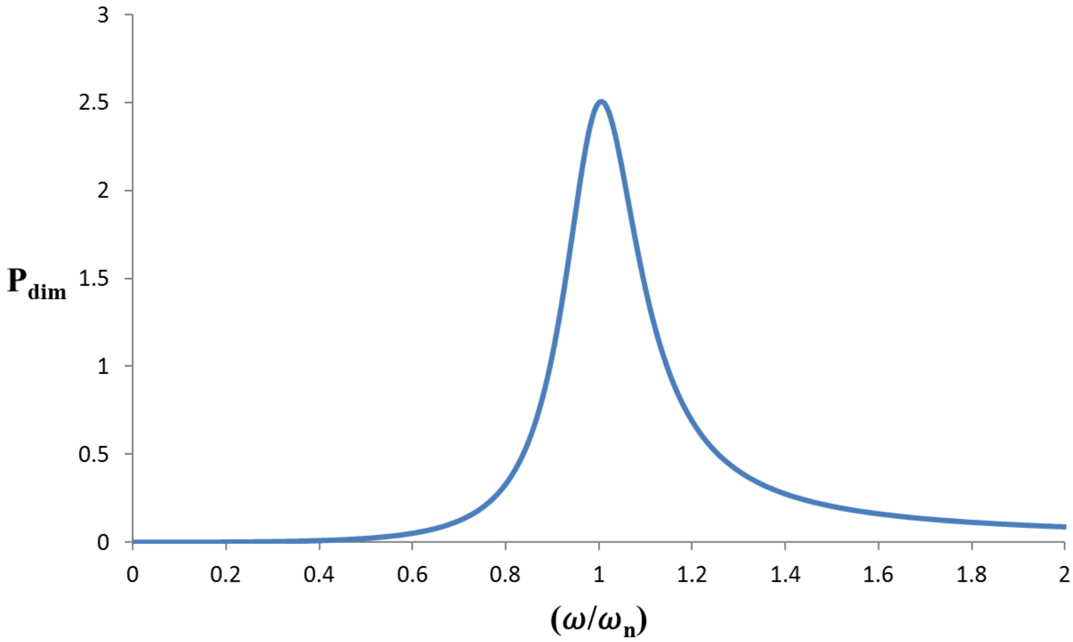

Figure 2: Dimensionless power vs normalised frequency from Eq. (12) with $\zeta = 0.1$

Understanding Eq. (12) is critical in maximising the power output of a (VBEH) device, power increases significantly with the amplitude of vibration and the frequency of vibration. A low damping factor is desirable however in reality zero damping is not possible for a steady state solution. The ratio of the vibration frequency to the natural frequency $\left(\frac{\omega}{\omega_n}\right)$ of the system reduces the denominator in Eq. (12) enhancing the power output at structural resonance. The output power is only harvested in the vicinity of the resonance of the device and minor deviations cause substantial power reduction as seen in Figure 2. Other modelling for vibration based energy harvesting devices can also be found in [6-10].

2.1 Device Considerations

The device considerations are the mass should be as large as possible within the available volume of the device, the displacement of the mass should be as large as possible within the available space and the spring should be designed so that the resonant frequency matches that of the excitation frequency. The source frequency and amplitude needs to be measured to determine the effectiveness of the device, Table 1 presents unwanted everyday vibration spectra which could effectively be harvested.

Table 1: Acceleration levels and peak forces from everyday applications [11]; Reproduced with permission from Elsevier

Vibration Source	Acceleration (m/s^2)	Frequency (Hz)
Car engine	12	200
Base of three-axis machine tool	10	70
Blender casing	6.4	121
Clothes dryer	3.5	121
Car instrument panel	3	13
Door frame just after door closes	3	125
Heating, ventilation and air condition (HVAC) vents in office buildings	0.2-1.5	60
Windows next to busy road	0.7	100
Compact Disk (CD) on notebook computer	0.6	75
Second story floor of busy office	0.2	100

2.2 Transduction Mechanisms

The main mechanisms used in the process of converting ambient kinetic energy into electrical energy are:

- Piezoelectric conversion: A piezoelectric material is used to convert the induced strain in the mechanical domain into electrical energy [12-17].
- Electrostatic conversion: The capacitive plates of a transducer fluctuate inducing a voltage [18-20].
- Electromagnetic conversion: Based on Faraday's law as a permanent magnet moves relative to a coil a current is generated inside the coil [21-24].

With the major drawback of conventional resonators only operating at or near resonance slight changes in the ambient vibration source are significant for effective performance; The coming sections will discuss the methods employed currently to enhance the power output and operating range of vibration energy harvesting devices.

3 AMPLIFICATION TECHNIQUES

Amplification techniques refer to the ability of the device to increase the source vibration for both enhanced power performance and operating range. This technique includes the use of mechanisms to increase the vibration amplitude in electromagnetic devices but also amplifying low environmental frequencies. The hybrid system has also been classed as an amplification technique as it achieves increased power using dual transduction mechanisms but only slightly increases operating bandwidth.

3.1 Mechanical Amplifier

A new development is to increase the effective vibration amplitude in devices to increase the relative displacement between magnet and coil through the use of mechanical amplifiers.

Such a design has been fabricated and experimentally tested for low amplitude (±1 mm) and low frequency (< 5 Hz) [25], the mechanism used to amplify the vibration has also been assessed on account of the mechanical gain factor that can be achieved. The mechanism will need to be able to accept any input amplitude but limit the output stroke to have a stable system. The designers use mechanism (d) from Figure 3 as the piston motion can convert the rotary motion to linear motion but also limit the output displacement as a function of the disc diameter used. For the device fabricated the mechanical gain factor is 4, the mechanical amplifier factor of 4 converts to a 16 times magnitude increase in total output power of the energy harvester. The results show an increase of power from 1.9 mW to 30 mW with the amplifier attached at 5 Hz shown in Figure 4. However the device has not been tested over larger frequencies which could be further explored to see the effect at higher frequencies, this technique also enhances the devices power density to 170 $\mu W/cm^3$.

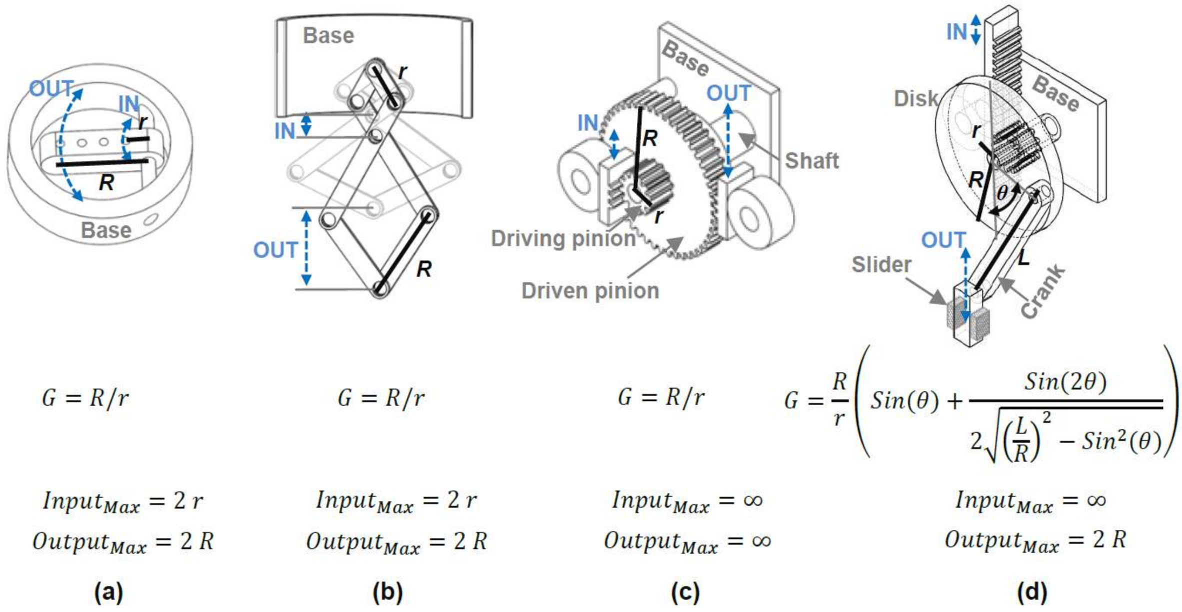

Figure 3:Schematic view of different mechanisms for mechanical gain: (a) lever, (b) scissors, (c) two rack pinion join, (d) rack-pinion paired with piston motion [25]

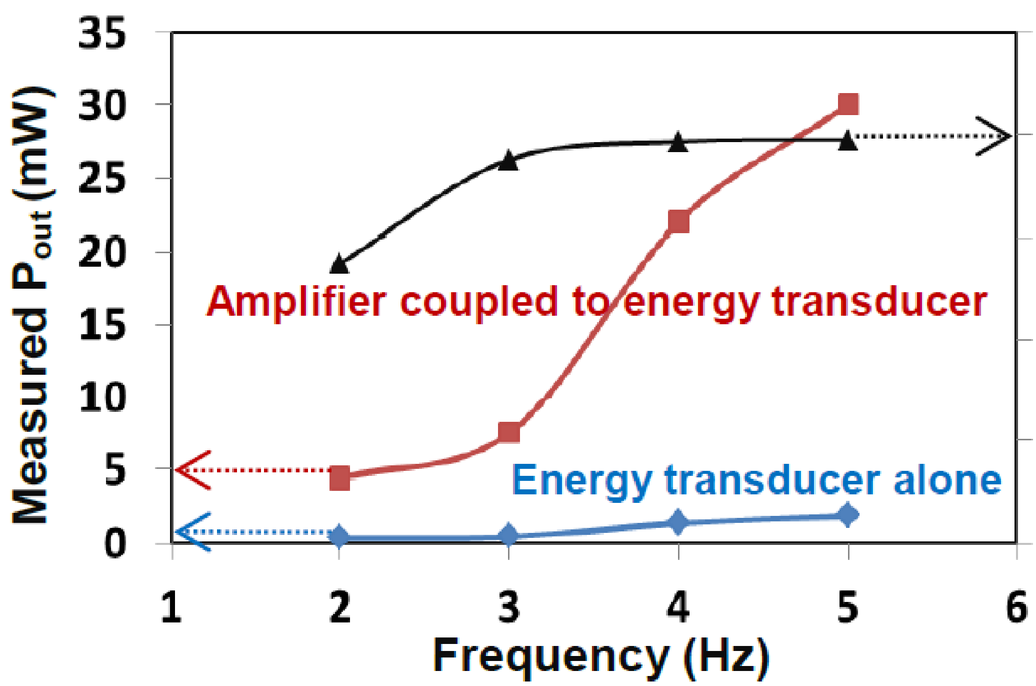

Figure 4: Output power with and without mechanical amplifier [25]

Another mechanical amplifier was been developed for use with a MEMS accelerometer [26], a mechanical gain factor of 40 has been achieved through the use of a lever mechanism.

The mechanical amplifier shows great potential in producing useful power output at low frequency excitations which is a major restriction for most other vibration energy harvesting devices, the only concern with the mechanical amplifier is the geometry required for both the amplifier and the increased relative displacement between structure and device. There is potential for the mechanical amplifier to be incorporated into more vibration energy harvesting devices in the future.

3.2 Frequency up Conversion

A problem for vibration energy harvesters is the amount of energy they can scavenge from low environmental excitations which can significantly reduce the devices performance. Frequency up conversion is a technique used for amplifying the source frequency to allow for effective energy harvesting from low frequency vibrations.

Such an approach has been modelled and experimentally evaluated, ten piezoelectric bimorphs are integrated into a windmill structure with an operational speed of 1-12 mph [27] a schematic is shown in Figure 5. The theoretical derivation was based on Timoshenko beam theory and the optimum results were obtained for a load of 6.7 kΩ and a wind speed of 10 mph resulting in an output power of 7.5 mW. It was also observed the saturated frequency of the windmill had a linear variation with the wind speed given by:

$$f\ (Hz) = -0.93 + 1.29v \qquad (13)$$

Where v is the wind speed in miles per hour. Priya states “Excellent matching was found between the experimental and calculated results”.

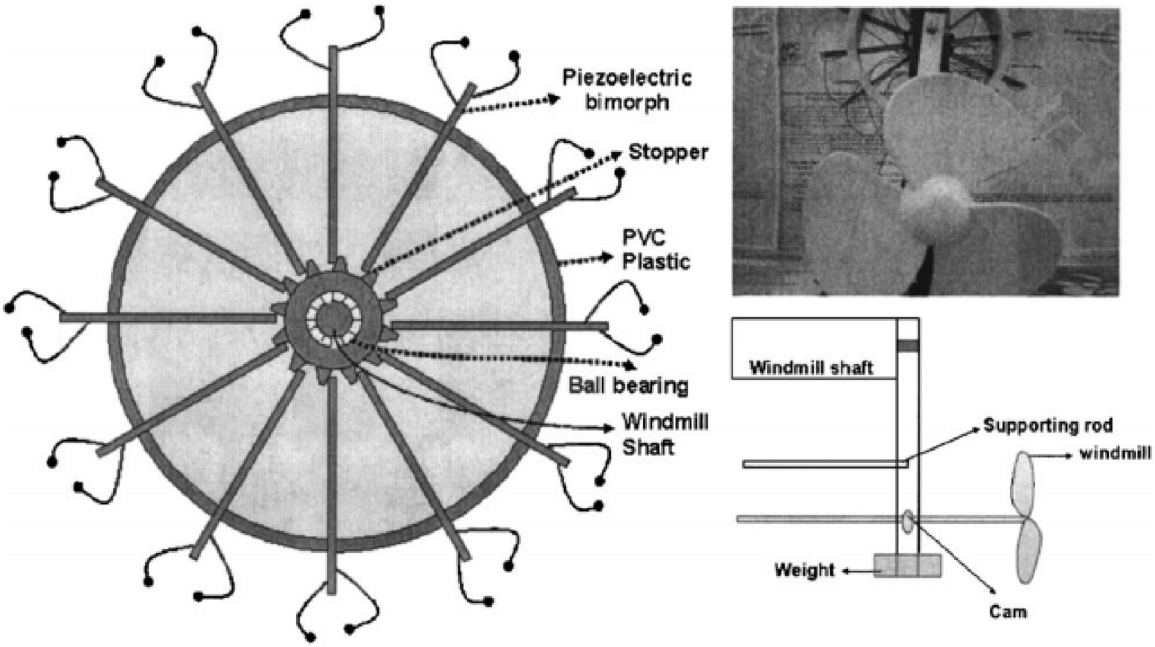

Figure 5: Piezoelectric windmill prototype schematic [27] ; Reprinted by Permission of AIP Publishing LLC

Due to the available power from an energy harvester being proportional to the vibration frequency this increases significantly with the surrounding excitation. A design employing frequency up conversion for a microelectromechanical system has been developed as an electromagnetic harvester for low frequency energy harvesting [28]. The device manufactured consists of 20 cantilevers connected in series; the micro generator has the dimensions 8.5 x 7 x 2.5 mm^3. The design is able to harvest 0.57 mV and 0.25 nW from a single cantilever.

Frequency up conversion has also been used for broadband vibration energy harvesting using magnetic excitation [29], the device remains stationary relative to the base motion. This work is also similar to a rack that periodically strikes a beam while it is vibrating [30].

A design using the magnetic actuation of a piezoelectric beam employing frequency up conversion tested on human motion found a maximum power output of 7 μW during running however quick degradation was found due to the bending beam [31].

A novel energy pumping based on frequency up conversion using electromagnetic induction has been able to effectively harvest ambient vibrations < 18 Hz [32], Figure 6 shows the effect of increased average power output at the orders of resonance for this device.

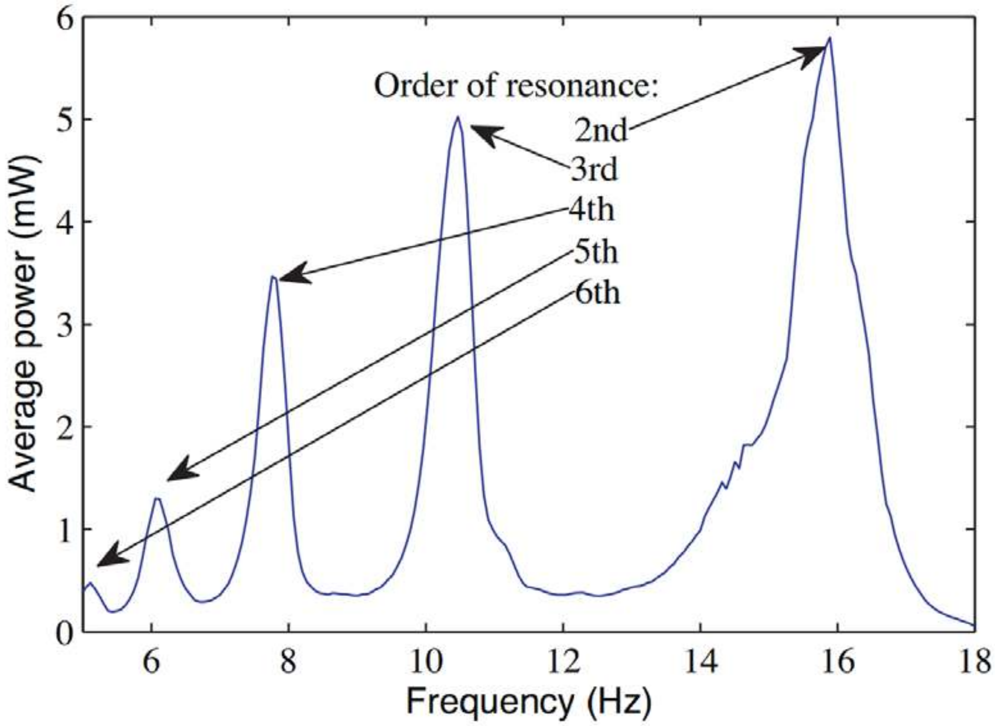

Figure 6: Average output power vs frequency [32]; Reproduced with permission from Elsevier

3.3 Hybrid Systems

A hybrid scheme can be a combination of piezoelectric, electrostatic and electromagnetic induction to further enhance the operating frequency of a vibration energy harvesting device. A hybrid device consisting of a cantilever beam with piezoelectric crystal and a magnet used as a tip mass that passes through a coil as the structure vibrates; a schematic view is shown in Figure 7 [33]. The natural frequency of such a system is given by:

$$f_i = \frac{1}{2\pi}\left(\frac{yi}{L}\right)^2 \sqrt{\frac{EI}{\rho A}} \tag{14}$$

Where i is the mode index, yi is the mode shape, L is the length of the beam, E is the young's modulus of elasticity of the beam, I is the moment of inertia, ρ is the density of the beam and A is the effective area of the beam.

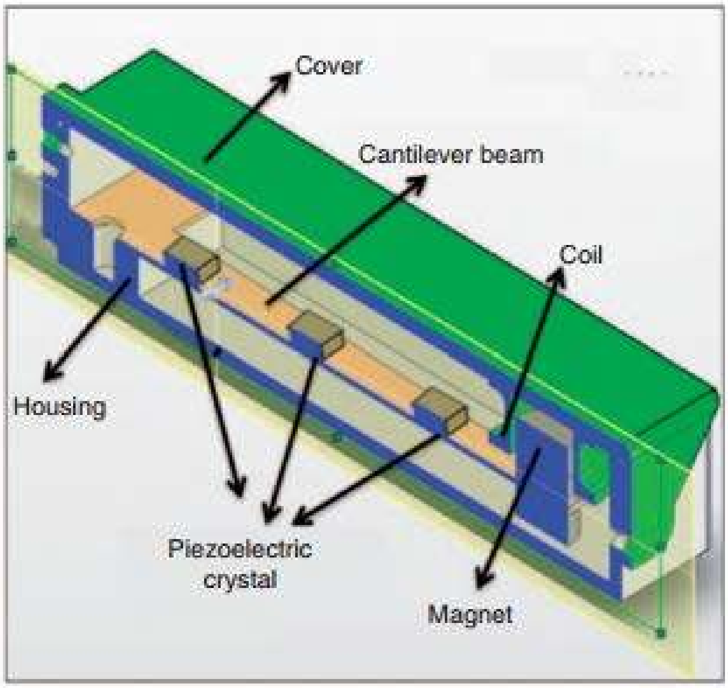

Figure 7: Schematic view of hybrid system [33]; Reprinted by Permission of SAGE

The result of the hybrid scheme found the electromagnetic contribution of the system produced higher output at lower frequencies while the piezoelectric components generated larger power output at higher frequencies. This allows for more energy harvesting over varying excitations from ambient vibrations. The volume of the device was 25 x 30 x 125 mm^3 and the maximum electromagnetic contribution was 0.25 W while the piezoelectric mechanism contributed 0.25 mW.

Work on the combined effects of a hybrid vibration energy harvester has also shown slight improvement in the operating frequency of the system as shown in Figure 8 [34]; This hybrid mechanism design is able to produce useful power output from 54-59 Hz.

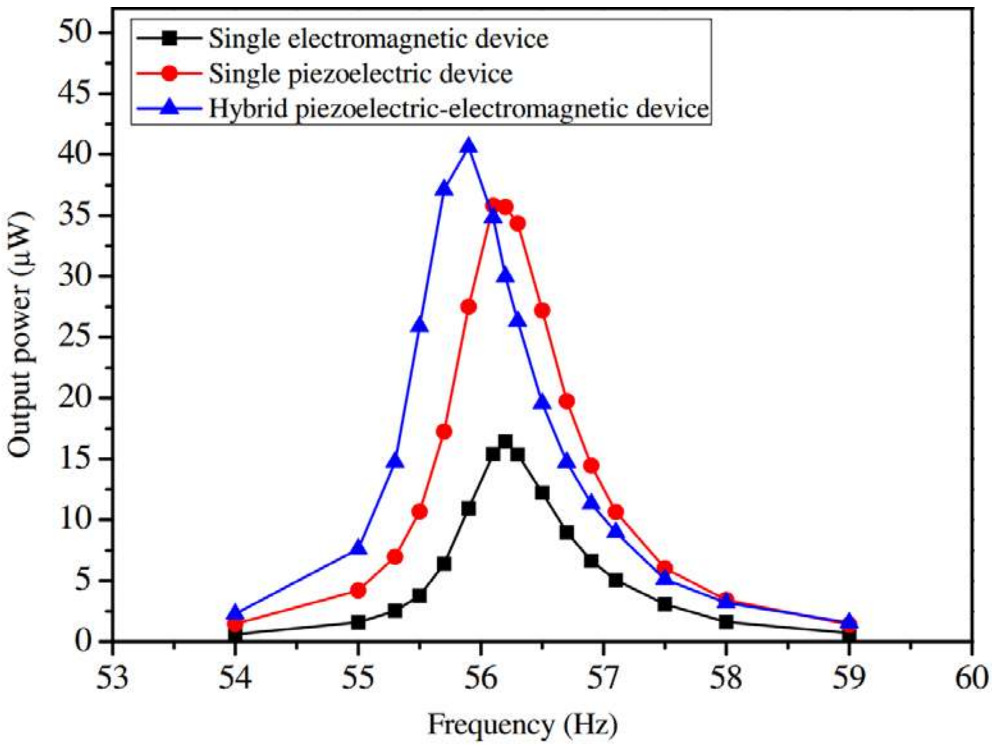

Figure 8: Output power vs excitation frequency [34]; Reproduced with permission from Elsevier

A design incorporating hybrid piezoelectric layers combined with electromagnetic induction has been fabricated and experimentally tested, the schematic is shown in Figure 9 [35].

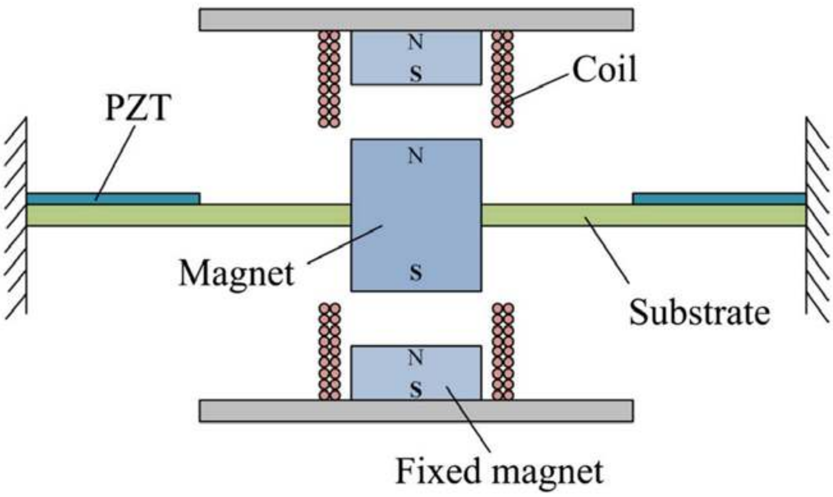

Figure 9: schematic design of nonlinear hybrid scheme [35]; Reproduced with permission from SPRINGER

This system is classed as a nonlinear hybrid system; for increasing base acceleration the effects of nonlinearity show a decrease in resonant frequency with increased output power and at the same time broaden the bandwidth of the device as seen in Figure 10. Other hybrid designs have also been considered and shown to improve the operating bandwidth of vibration energy harvesting devices [36, 37].

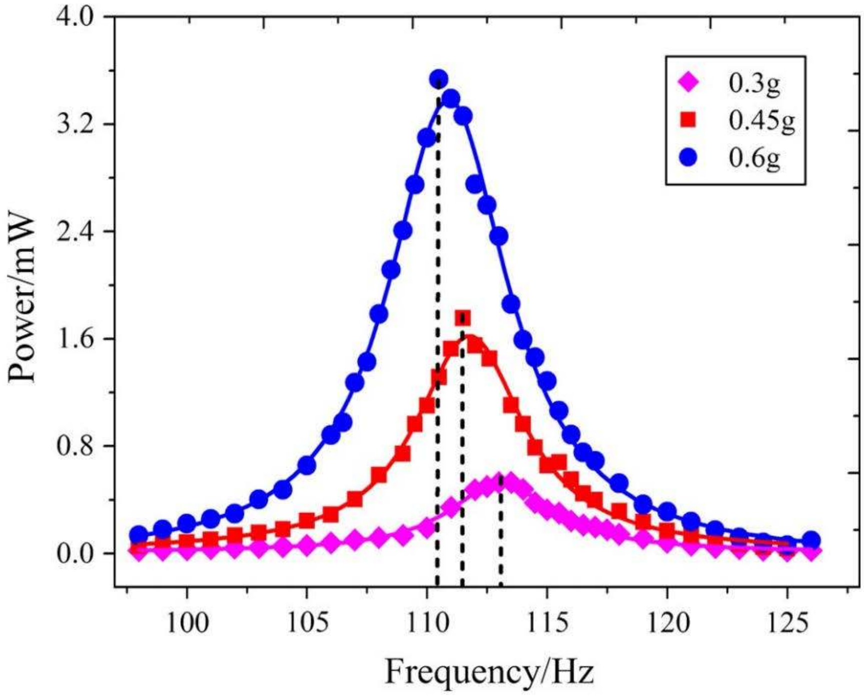

Figure 10: Output power from combined hybrid harvester with different acceleration loadings [35]; Reproduced with permission from SPRINGER

4 RESONANCE TUNING TECHNIQUES

With the natural frequency of a system given by $\omega_n = \sqrt{\frac{k}{m}}$, resonance tuning can be considered to either effectively have changing masses in a system such as multiple resonant systems working together to broaden the effective operating range and increase the power output. These systems can contain either multiple masses on single cantilever beam elements through to the use of many individual systems creating multimodal arrays. The other method of resonance tuning is done by applying different mechanisms to change the effective device stiffness. Stiffness tuning techniques can include the use of applying preload to the device, the addition of a magnetic stiffness term or changing the load impedance in the extraction circuit.

4.1 Multiple Degrees of Freedom

Increasing the effective operating bandwidth of a vibration energy harvester can be done by increasing the number of masses in the system, the adverse effect will increase the number of resonance points in the system. These extra masses can be connected in series to increase the power output of the device, multiple degrees of freedom refer to the addition of extra masses on single beam elements.

Such a system has been theoretically modelled where a dual mass vibration energy harvester connected in series is analysed [38]. This type of harvester is suited for harvesting more energy over conventional single mass devices; this type of device still works on the same principal as conventional energy harvesters however the increase in resonance points allows for more operating frequencies. With a two mass system the condition now exists for two local optimums to exist for maximum power harvesting. The effects of electrical damping, mass ratio and tuning ratio are also explored in detail to optimise such a potential device, the effect of base excitation and direct excitation is investigated and it is shown for a two mass harvester both these conditions come to the same power output formula given by:

$$\overline{P_{ave}} = \frac{P_{ave}}{X_0^2 \omega_1^3 m_1} = \frac{\mu f \zeta_e \alpha^6}{\left(\alpha^4 + f^2 - \left((1+\mu)f^2 + 1\right)\alpha^2\right) + 4(\zeta_m + \zeta_e)^2(\alpha f - (1+\mu)\alpha^3 f)^2} \quad (3)$$

where X_0 is the amplitude of vibration ζ_e and ζ_m are the electrical and mechanical damping coefficients respectively,$\mu = \frac{m_2}{m_1}$, $\alpha = \frac{\omega}{\omega_1}$ and $f = \frac{\omega_2}{\omega_1}$. The device could have two local optimums. An experimentally validated double mass piezoelectric cantilever beam also shows dual resonance peaks for broadband energy harvesting [39].

A separate dual resonating system has been investigated where the device consists of two different resonating cantilever beams made of permanent magnet and coil as seen in Figure

11 [40]. Matlab-Simulink numerical solutions were carried along with ANSYS finite element analysis; these numerical results are compared to experimental results obtained. Under the acceleration loading of 0.8 ms^{-2} the experimental output voltage is within good agreement of the simulated results. A 58.22% improvement is achieved between the intermediate regions of the two cantilever micro-generators.

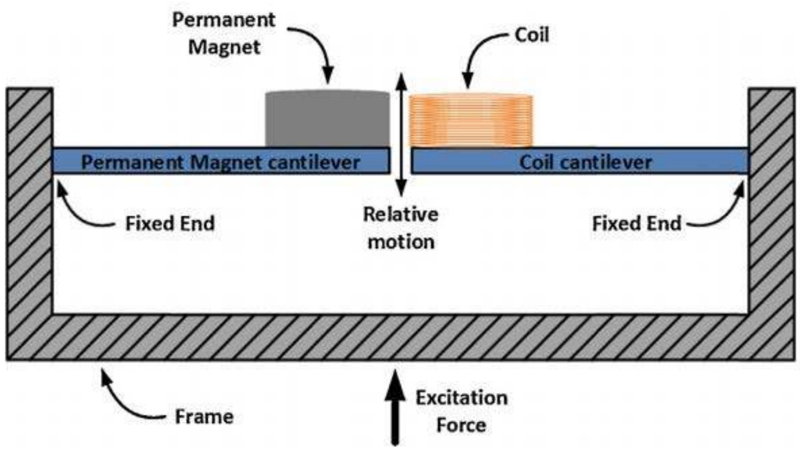

Figure 11: Dual resonating electromagnetic generator [40]; Reproduced with permission from Elsevier

Increasing the number of resonant peaks can also be done through the use of multilayer beams with rigid masses attached between the beams [41]. The attachments of these masses are used to tune the frequency of the device. Selecting appropriate positions of the masses can achieve multiple modes, create close resonance peaks and increase the power output of the device whilst enhancing operating bandwidth.

4.2 Multimodal Arrays

Increasing the effective bandwidth and total power output of the vibration energy harvesting device can be achieved through multimodal arrays that target different frequency sets with various single systems designed to resonate at slightly different frequencies. This concept of consistent structures is called a mechanical band pass filter and can be utilised for scavenging vibration energy over larger effective bandwidths.

A systematic methodology for the design and implementation of such an array has been conducted and extensively reviewed by Shahruz [42-45]. The type of system is an array of cantilever beams with slightly different tip masses and beam dimensions being used for close resonant peaks between each individual resonating cantilever demonstrated in Figure 12. Piezoelectric film is used as the mechanism to harvest the vibration energy.

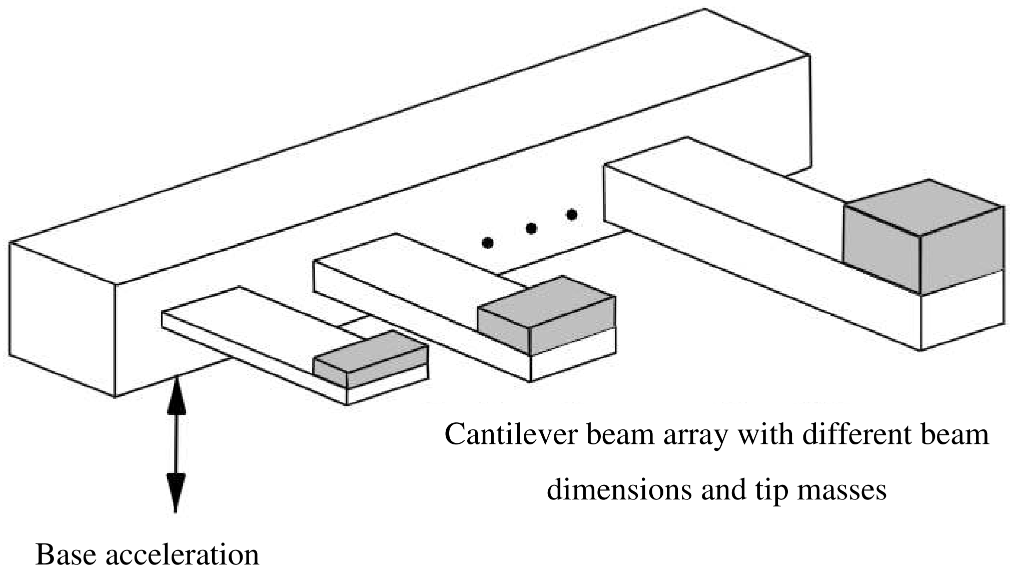

Figure 12: Multimodal array structure to effectively harvest energy over larger bandwidth [43]; Reproduced with permission from Elsevier

Other MEMS base generator arrays have been developed with extended operational bandwidths [46], Such an array would have an increased number of resonances and all individual transfer functions contribute to the total power harvested.

Another study was conducted on multi-modal arrays with slightly different tuned resonators and multiple piezoelectric bimorphs where the overall power output has a more effective bandwidth and increased total power harvested [47]. Each individual power output from each bimorph contributes to the overall power and the effective bandwidth becomes 92.5~110 Hz, however, this method requires more complex designs and multiple cantilevers with different geometries; moreover, the electrical circuit also becomes more complex with this type of design.

A nonlinear multi frequency converter array using four cantilever piezoelectric beams has also been fabricated and results show an increased operating range for array's with differently tuned resonators [48].

4.3 Preload

A technique used to adjust the performance of a piezoelectric bimorph vibrating in flexural mode through an applied axial preload has been developed [49], this is a useful technique for scavenging ambient vibration energy over broader frequency bands. The analysis conducted also shows resonance occurs when the natural frequency of the bimorph is adjusted through preloading. This can effectively increase the overall power density of the device. A simplified piezoelectric harvester is modelled however it goes into considerable detail for the preloading mechanism to provide a framework for further developments.

Researchers have also designed, developed and tested a resonance tuneable vibration energy harvester which utilises axial compression to lower the natural frequency of the overall device [50]. The natural frequency of this system is comprised of the transverse stiffness of the cantilever beam containing a bimorph element and the application of axial compressive preloading destabilizes the bimorph reducing its transverse stiffness. The results for this particular device determined that an axial preload can reduce the natural frequency of the scavenging device up to 24% while increasing the coupling coefficient by 25%. The device is also shown to have a larger effective operating region in producing a useful amount of output power. Results show that a proof mass of 7.1 g was able to produce 300-400 µW in a frequency range 200-250Hz while a 12.2 g mass produced 360-650 µW from 165 to 190 Hz. Figure 13 demonstrates the maximum power output against the adjusted resonance frequency with power ranging from 300-400 mW for a frequency range of 195-250 Hz. A closed loop controller could be utilised to control the effective preload so that a "smart device" could pursue the optimal preload for the most effective power output.

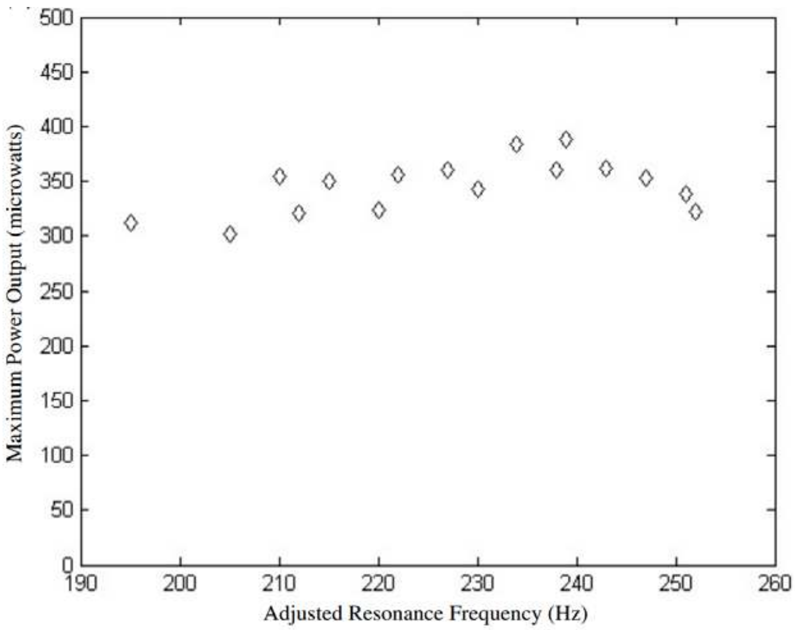

Figure 13: Maximum output power against tuned resonance frequency for 7.1 g tip mass [50]

The effects of preload on the effective operation of vibration energy harvesters from a cantilever beam has been investigated [51]. This converter consists of a piezo polymer cantilever with additional arms to adjust the axial preload at the tip of the beam as seen in Figure 14. The axial preload is used to effectively shift the natural frequency of the structure to enhance its operating range. There is potential for this application with the operating range altered from 380 to 292 Hz in one experiment. Eichhorn also applies a tensile preload in another experiment and is able to increase the natural frequency, the effective operating range increases from 440-460 Hz. By applying a compressive axial preload a frequency shift of 22% was achieved and the tensile equivalent produced only a 4% change in the devices effective resonating frequency.

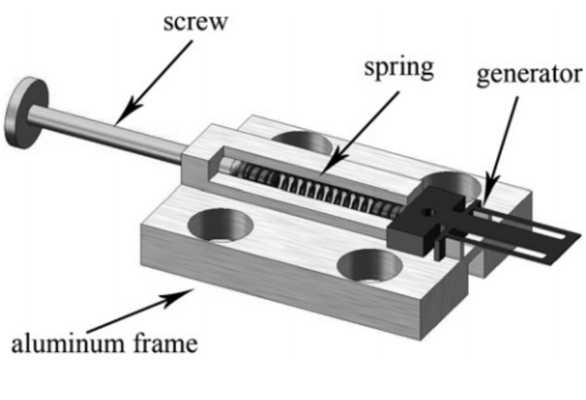

Figure 14: Draft design for the compressive axial loads [51]

4.4 Extensional Mode

Recently a new mechanical tuning method by deforming the piezoelectric element primarily in plane extension, where bending effects can be ignored has been developed [52]. The device developed operates with a suspended mass with two piezoelectric sheets a cross section can be seen in Figure 15. The mechanism is frequency tuneable by an adjustable link that pre tensions both sheets of piezoelectric material. The extensional mode resonator is able to effectively exploit a nonlinear force deflection characteristic as seen in Figure 16; this particular device is able to adjust the frequency range by 150 Hz.

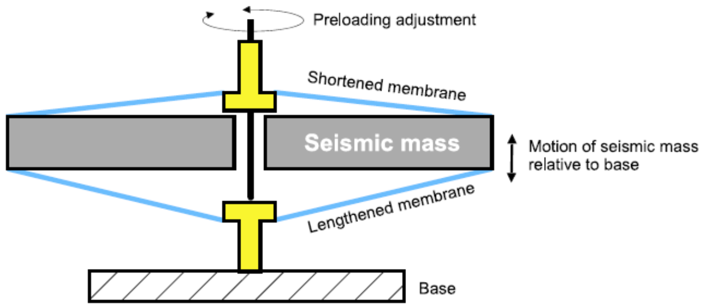

Figure 15: Cross section of the extensional mode resonator (XMR), [52]; © IOP Publishing. Reproduced with permission. All rights reserved

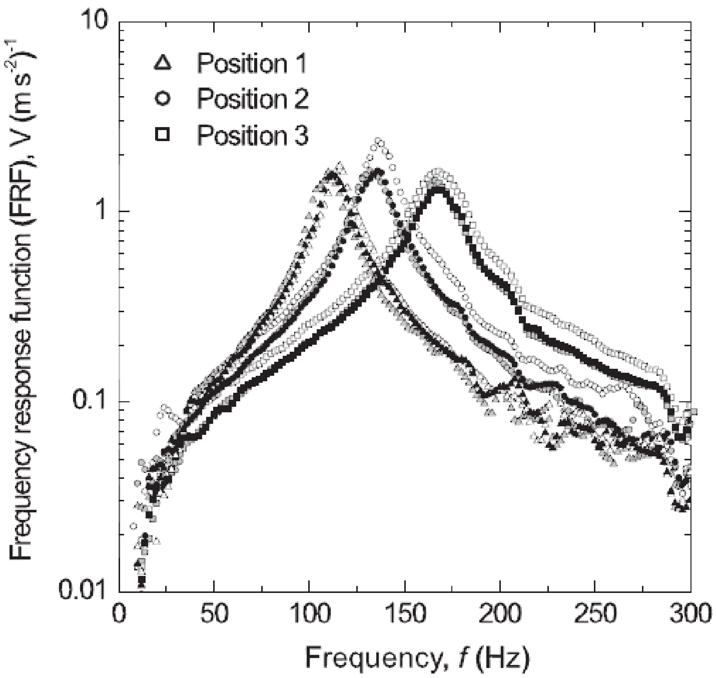

Figure 16: Frequency response function from experiments with different adjustment positions [52] ; © IOP Publishing. Reproduced with permission. All rights reserved

The extensional mode resonator (XMR) has also been extended as a continuation of the previous work developed by Morris [53]. This paper predicts the output power harvested as a function of the frequency and amplitude of the external vibration, the elastic, piezoelectric material properties and the device geometry. The extensional mode resonator has shown good results between the experimental data and theoretical predictions, results for 0.5 g acceleration produced 3-4 mW whilst for 1 g acceleration the peak power produced was 9 mW. The model and experiments for the XMR both indicate that the damping has the greatest influence on the device performance.

4.5 Magnetic Tuning

Magnetic techniques for increasing the resonance frequency through tuning can also be adopted with slight changes in geometry; the effective natural frequency of the vibration energy harvester can be modified.

A piezoelectric cantilever beam with a natural frequency of 26 Hz has been modelled and fabricated; permanent magnets are fixed on either side of the cantilever tip mass and apply an equivalent repulsive and attractive force to the structure as seen in Figure 17 [54]. The change in the structures natural frequency comes from the induced magnetic force K_{mag}, the effective stiffness of the system becomes:

$$K_{eff} = K_{beam} + K_{mag} \tag{5}$$

This can also be modelled as a lump mass system with a linear spring and adjustable spring, with the results shown in Figure 18. The volume of the device used was 50 cm^3 and the power harvested is in the range of 240-280 μW, when the device is tuned accordingly with acceleration amplitude of 0.8 ms^{-2} applied the effective operating bandwidth is 22-32 Hz.

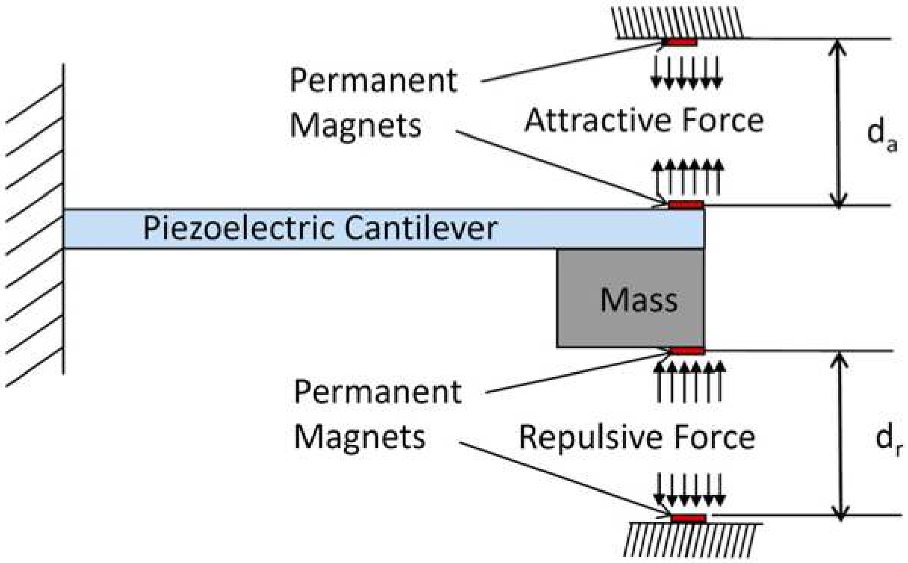

Figure 17: Cantilever with tip mass and magnetic resonance tuning [54];

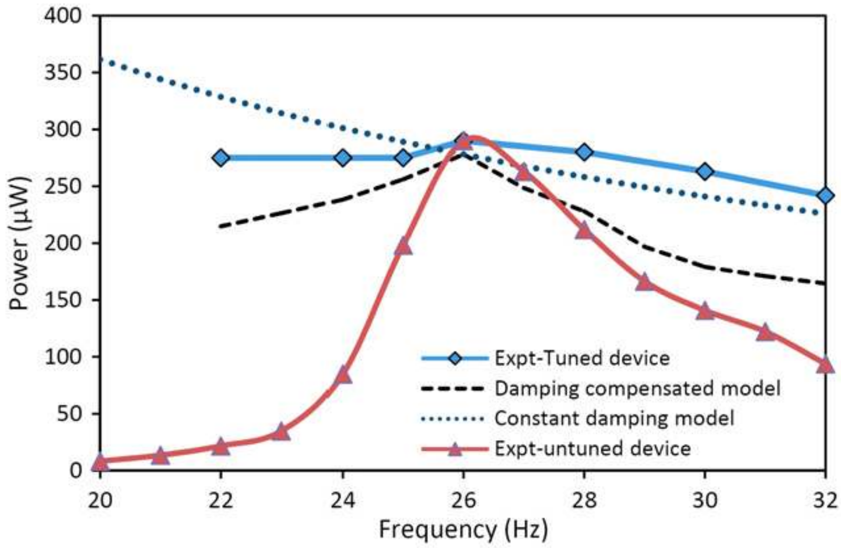

Figure 18: Power vs frequency for tuned and un-tuned device [54];

Another magnetically tuneable design has been considered in which the two magnets adjust passively to tune the resonant frequency of the device [55]. From the experimental work the device was capable of self-tuning in the range of 4.7 to 9 Hz with magnet gap difference from 66 to 16.7 mm. The authors also state however “the device is effective only for single frequency excitation schemes, and hence is not applicable for multi-component or broadband excitation”.

4.6 Complex Load Topology

The bi-directional tuning of an electromagnetic vibration energy harvester incorporating FR4 using laser micromachining has been evaluated [56]. In this new design four electromagnetic energy harvesters are fabricated with different spring configurations for different natural frequencies. This is used in combination with two different loads for capacitive and inductive tuning; the tuning approach can be seen in Figure 19. The theoretical model developed demonstrates the tuning range widens with increasing load resistance for capacitive tuning and broadens with decreasing load for the inductive tuning method.

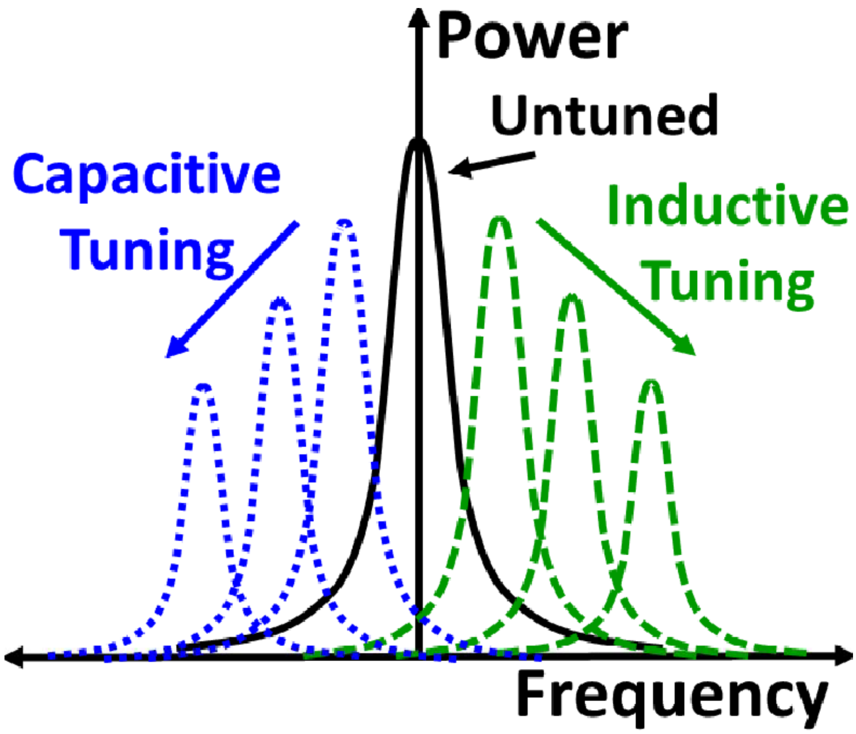

Figure 19: Proposed bidirectional tuning by changing the load impedance [56]; Reproduced with permission from Elsevier

5 NONLINEAR TECHNIQUES

A promising means for increasing the effective operating bandwidth of a vibration energy harvester is to utilise non-linear stiffness attributes from the geometry of the device, these can include the use of magnets and changes in the effective lengths of beams.

5.1 Mono/Bistable Systems

Nonlinear oscillators have received significant attention over the last two decades due to the increased bandwidth but also increased power generation compared to that of a linear system. Nonlinear oscillators are typically modelled using the Duffing equation (Eq. 6) with cubic non linearity however it is important to note the material stiffness is not changing just the effective stiffness of the device.

$$m\ddot{x} + c\dot{x} - kx + k_3x^3 = Fcos\omega t \tag{6}$$

A bi stable energy harvester can be modelled with $k > 0$ presented in the Duffing equation, the effective bandwidth of the vibration energy harvester can be extended when they possess nonlinear potential functions. Detailed modelling of nonlinear vibration energy harvesters can be found in [57-60]. A comparison between bi-stable and mono-stable harvesters found that at small base accelerations the mono-stable harvester is more optimal however bi-stable harvester with large base accelerations need to be coupled with appropriate potential functions [61, 62], but in general bi-stable harvesters have a broader bandwidth [63] and their harvester output power is not influenced under white noise [64, 65]. In some regions the nonlinear energy harvester can be disadvantageous for the system compared to its linear counterpart and the opposite is also true, nonlinear coupling needs to be correctly integrated into the system [66]. Theoretical modelling and experimentation analysing the triple well potential function induced by a magnetic field has shown the tri-stable design can attain higher energy inter-well oscillations and the tri-stable device has a broader frequency range imposed from low excitation levels [67].

One possible design of such a harvester has been considered for a cantilever with magnets attached [68]. The experiments conducted excite the base structure causing the cantilever beam to vibrate in the transverse direction using an electrodynamic shaker; accelerometers have been placed on the tip mass and base structure to obtain the voltage output of the coil. Gaussian white noise has also been used as a source of vibration using a linear band pass filter. This design of harvester is able overcome the one resonant frequency where slight shift would cause significant output power reduction. The effect of magnetic induced nonlinearities in a cantilever beam with a piezoelectric layer has also been numerically and experimentally investigated [69, 70]. Other work to find nonlinear magnetic coupling in a piezoelectric energy harvester through a polynomial function also has broadening effects [71].

A levitated magnet has been shown to give a similar non-linear effect with its output relative displacement and power. Such a design using three magnets in a tubular housing unit, two of the permanent magnets are fixed while the magnet in the middle levitates between the other two and is subject to relative displacement when the base magnet is subject to environmental vibrations; the design schematic is shown in Figure 20.

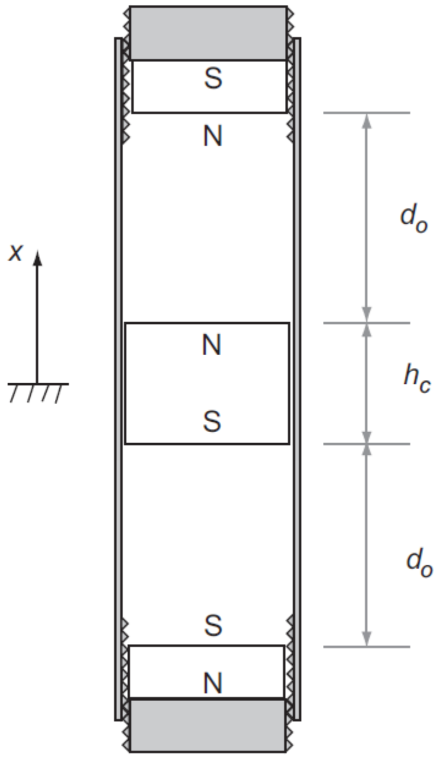

Figure 20: Magnetic levitation energy harvester [72]; Reproduced with permission from Elsevier

Such a device has been fabricated which can be implemented in MEMS and macro scale devices [72]. This is particularly well suited for powering wireless sensors in hostile surroundings to send data from wireless devices. This technique allows a nonlinear stiffness to be achieved which has been experimentally derived as a function of the separating distance between the centre and bottom magnet. A cubic power fit has been applied to the data and for a single degree of freedom system this becomes the Duffing oscillator, however in the analysis gravity is also included in (Eq. 6). A perturbation technique known as the method of multiple scales is used to solve this Duffing oscillator, an amplitude frequency response function is obtained with 6 roots corresponding to stable, unstable and periodic solutions. The detailed analysis can be found in the paper for completeness however the results presented are in terms of relative velocity (mm/s). An extensive detail of different vibration amplitudes and damping is investigated and the linear natural frequency of the system is experimentally derived to be 42.36 rad/s, a comparison between the linear and corresponding nonlinear system is investigated. The experimental setup was conducted with a shaker, accelerometer, computer control system and the centre magnets corresponding relative velocity is measured with a laser vibrometer. The experimental results and theoretical results show good agreement with one another, with forcing amplitude of F_1 = 8.4 ms^{-2}; the device has an enhanced operating range from 6-12 Hz as seen in Figure 21. The effects of Duffing type and Coulomb damping non-linearities has also been investigated for random excitations for the levitated magnet system [73].

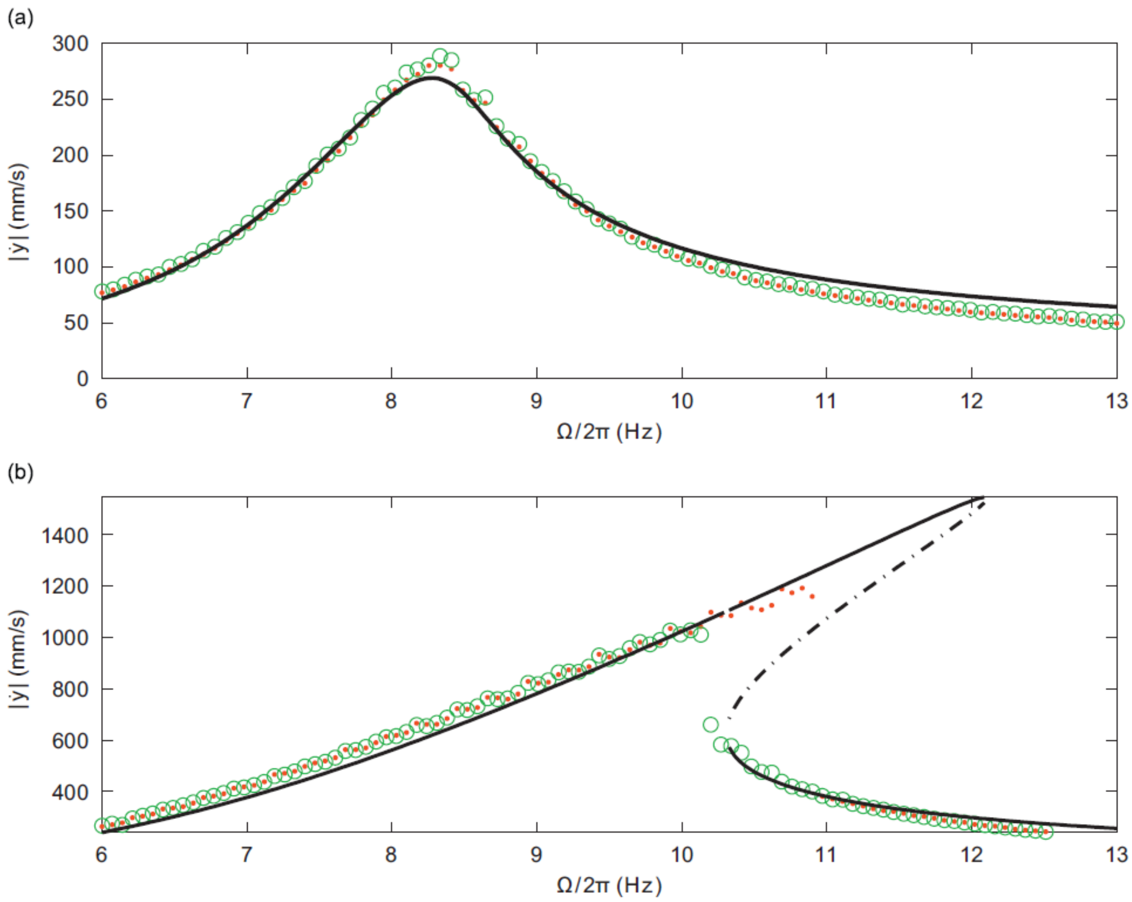

Figure 21: Experimental velocity response amplitudes from forward (red dots) and reverse frequency sweeps (green circles) are compared with theory. Theoretical predictions are separated into stable solutions (solid black line) and unstable solutions (dashed black line). Graph (a) shows results for $F_1 = 2.1\,\mathrm{ms}^{-2}$ and the results of graph (b) are for $F_1 = 8.4\,\mathrm{ms}^{-2}$ [72]; Reproduced with permission from Elsevier

The levitated magnet has also been theoretically analysed, fabricated and experimentally evaluated [74], which is modelled both as a linear and nonlinear resonator as a single degree of freedom system. The damping of this system is found through a unit step input and applying a logarithmic decrement factor, the frequency response functions also show the same nonlinear power output shape as Figure 21. A quality factor of 0.42 has been achieved by measuring the natural frequency and the corresponding half-power bandwidth with an optimal coil geometry to minimise electrical damping in the coils [75]. For a mono-stable levitated magnet system for more effective vibration energy harvesting; ways to mitigate eddy current and optimal coil design for enhanced transduction has also been investigated [76].

As mentioned previously the effects of preload can have an improved effect on a vibration energy harvester's bandwidth. A device is fabricated representing a cantilever beam with a piezoelectric substrate layer attached [77]. The device is able to effectively work nonlinearly and subsequently the amplitude and voltage frequency curves are leaning towards the right for stiffness hardening. Masana and Daqaq also suggest that the hysteretic characteristics of the frequency response function can sometimes be beneficial in particular when the external vibration has time varying frequency. The device should not be tuned to the frequency of excitation rather it should be tuned to a slightly lower frequency for this axially loaded member. The analysis used for the theory is also based on the method of multiple scales and the results between theoretical calculations and experimentally obtained are within good agreement.

An "M" shaped oscillator has also been fabricated and tested with clamped ends the schematic of this design can be seen in Figure 22; this device also exhibits spring hardening effects when base excitation is applied to the structure [78]. The use of a plate bonded with piezoelectric material and bistable nonlinearity has also been experimented, to investigate the harvestable energy that can be exploited [79].

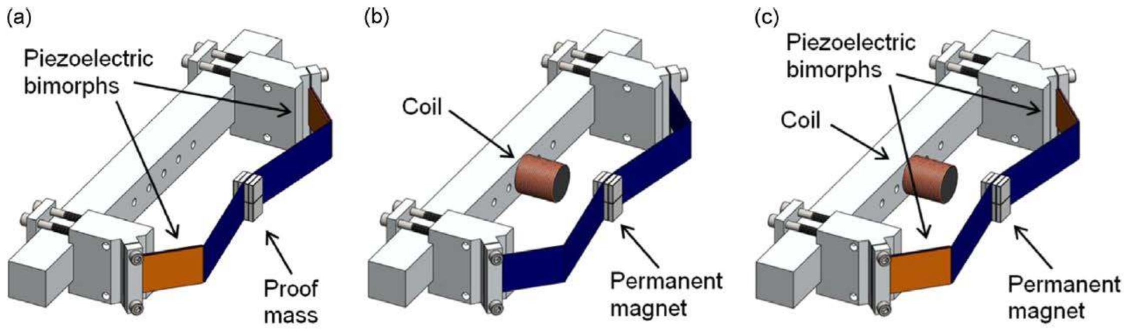

Figure 22: M shaped piezoelectric and/or electromagnetic energy harvester (a) piezoelectric patches attached (b) coil magnet arrangement (c) combination of (a) and (b) [78]; Reproduced with permission from Elsevier

Nonlinear effects can be seen to have an improved effect on the nonlinear resonance bending the response curves to the right for hardening systems. However softening systems can also be employed to bend the curves to the left also creating wider device operating bandwidth and enhanced power output.

Such a softening stiffness device has been fabricated, modelled and experimentally evaluated [80], the arrangement used consists of a permanent-magnet/ball bearing arrangement with a coil. The device is modelled as a duffing oscillator also with quintic non linearity and is solved using homotopy analysis method. In Figure 23 results show good accuracy between theory and experiments with the energy harvester able to effectively scavenge 16.4 mW at 14.2 Hz with a 400-milli-g base excitation.

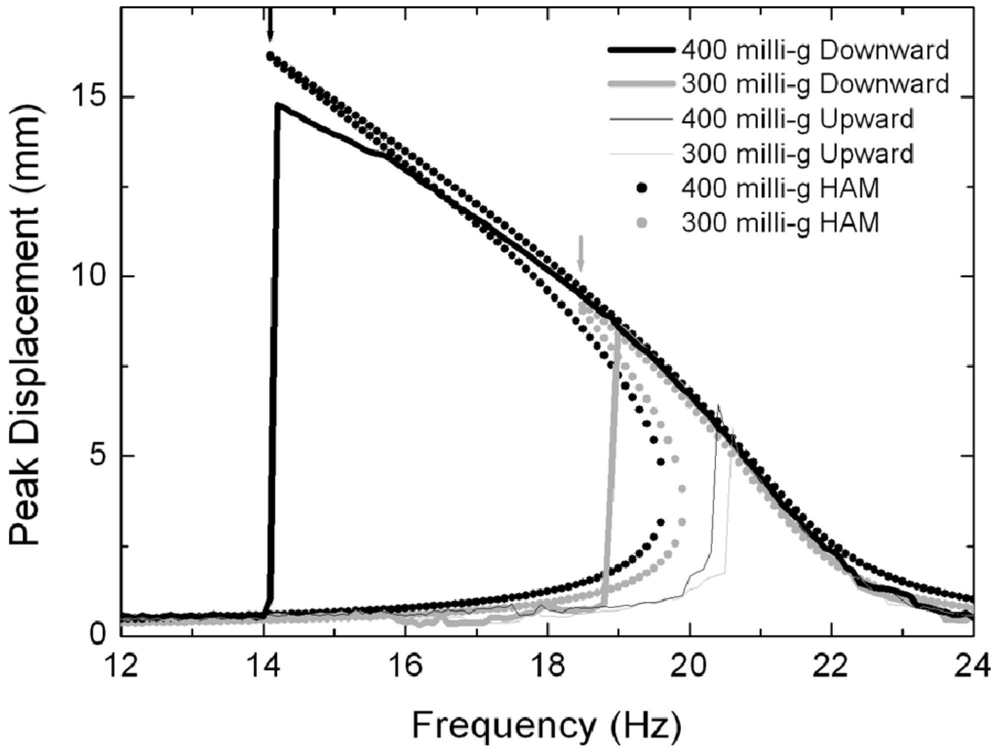

Figure 23: Comparison of model and experimental displacement measurements [80]
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A nonlinear stiffness has also been achieved for a low level ambient kinetic energy harvester using dual charged electret plates [19]. This nonlinear stiffness is important for increasing the operating bandwidth of the device which has a total volume of 0.12 cm^3. These out of plane electrostatic vibration energy harvester is fabricated by CMOS silicon micromachining technology**.** Higher amplitude of vibration increased operational frequency by 10 Hz for 0.3 g to 0.5 g corresponding bandwidth was 75-80 Hz and 65-80 Hz respectively which can be seen in Figure 24.

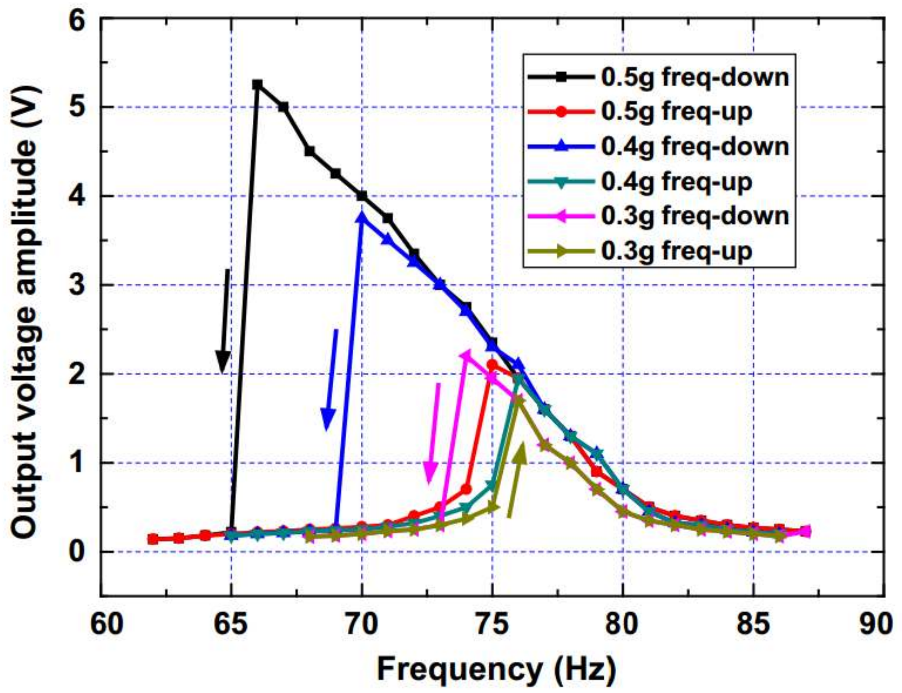

Figure 24: Measured output Voltage versus frequency of dual out of plane electret plate [19]; Reproduced with permission from Elsevier

5.2 Stochastic Loading

Stochastic resonance has also been investigated as a tool for nonlinear resonance [81], this normally unwanted noise has been used as a tool to improve the vibration energy harvester. A clamped-clamped beam model is derived for simplicity and is analysed, the conclusions are that while the device may be more complex mechanically the energy extracted can be significant and this type of vibration energy harvester will be further analytically and experimentally investigated. A bistable vibrating system can be amplified with stochastic resonance for certain dynamic conditions [82]. Magnetic nonlinearity stiffness has been introduced to a bi-stable system cantilever piezoelectric beam using MATLAB Stochastic Differential Equation (SDE) toolbox with white-noise added which also shows improved broadband over the linear counterpart [83, 84].

5.3 Mechanical Stoppers

A new development into broadening the operating region of vibration energy harvesters is to incorporate mechanical stoppers on either ends of a cantilever design particularly using piezoelectric elements. As the cantilever beam vibrates it strikes the stoppers losing energy on impact but enhancing bandwidth performance. An advantage of mechanical stoppers over electrical circuits is that they do not require any more complex circuitry in their interface and also the need to be able to self-power and self-activate. This complex strategy for switching circuits can be disregarded when using simple mechanical stoppers to limit the displacement of the cantilever beam which is driven by the excitation of vibration itself. The use of mechanical stoppers can result in nonlinear energy extraction which is desirable for effectively collecting energy over broader frequency ranges.

A piezoelectric cantilever beam structure utilising mechanical stoppers has been developed [85], this device introduces geometrical nonlinearity by means of mechanical stoppers and a self-synchronised nonlinear energy extraction circuit. The use of the mechanical stoppers is to enlarge the effective oscillating bandwidth and stoppers can be used to prevent damage to the piezoelectric elements when the oscillating structure is attacked by shock forces. The use of stoppers is also beneficial due to their simple electromechanical design which can be easily manufactured and well suited for MEMS implementation. Experimental results show an increased effective bandwidth of the device for a clamped free beam which is important for practical applications of vibration energy harvesters. Figure 25 demonstrates the effect of the stoppers on the system while a decrease in the maximum amplitude is seen; the operating bandwidth has increased by 20% which is far more desirable as slight shifts in the vibrating frequency can be harvested without needing a control system to change the effective natural frequency of the energy harvester.

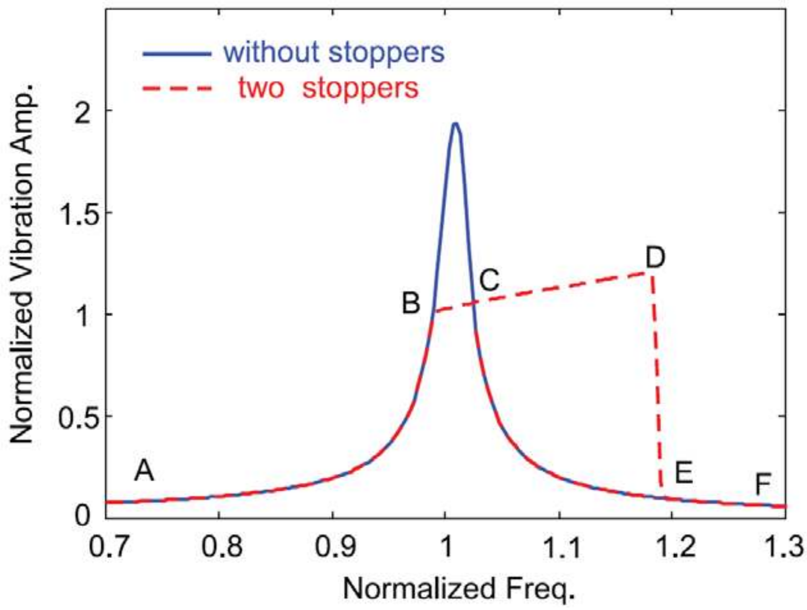

Figure 25: Normalised vibration amplitude with and without stoppers [85]; Reprinted by Permission of SAGE

A mechanical diode-less voltage rectifier has been developed using two bi-stable cantilevers to generate a voltage through piezoelectric elements due to the induced vibration from the environment [86]. The device developed is particularly suited for rectifying very low voltages which is well suited for micro and nano vibration energy harvesters, as the device decreases in volume there is a reduction in output voltage.

A similar system as [86] was developed that is particularly suited for smaller MEMS and NEMS applications, this structure is shown in Figure 26 [87]. The output voltage of the harvester will be small and will be wasted if the diode threshold cannot be overcome, the experimental implementation of this system demonstrates the ability to effectively collect and store the energy that would have been wasted from other approaches.

The inherent effect the stoppers have on the system with configuration 1 corresponding to one stopper and configuration 2 being two stoppers utilised as seen in Figure 27 can affect the amplitude and frequency of harvested energy [88]. Configuration 1 is seen to have higher amplitude of output power however the bandwidth is shorter than that of configuration 2. Results show the bandwidth for two stoppers having an effective bandwidth of 30-48 Hz and the corresponding optimal power output ranges from 34 to 100 nW with a base acceleration of 0.6 g and the distance between top and bottom stopper being 0.75 and 1.1 mm respectively. Liu also notes the operating frequency can be optimised by adjusting the mechanical stopper distance however, this has not been investigated.

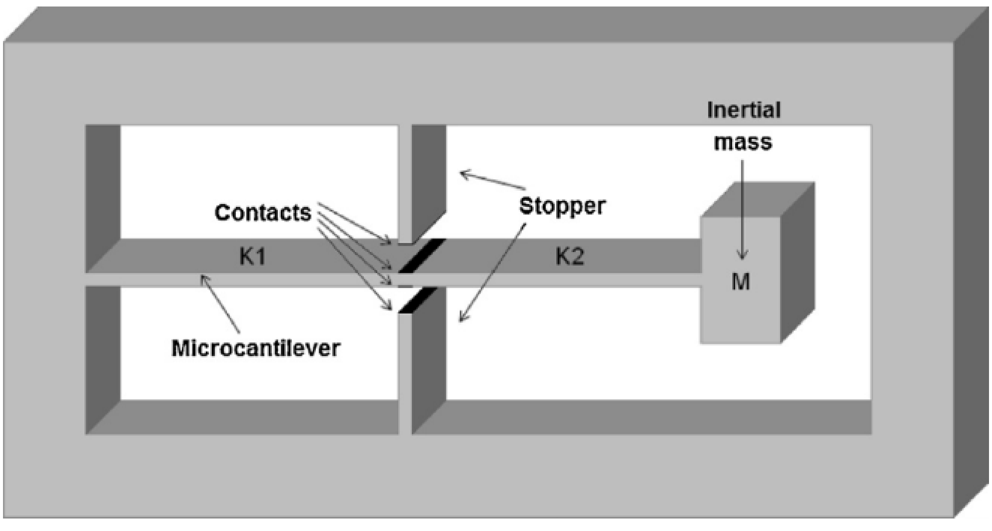

Figure 26: Structure of mechanical switch [87] ; Reproduced with permission from Elsevier

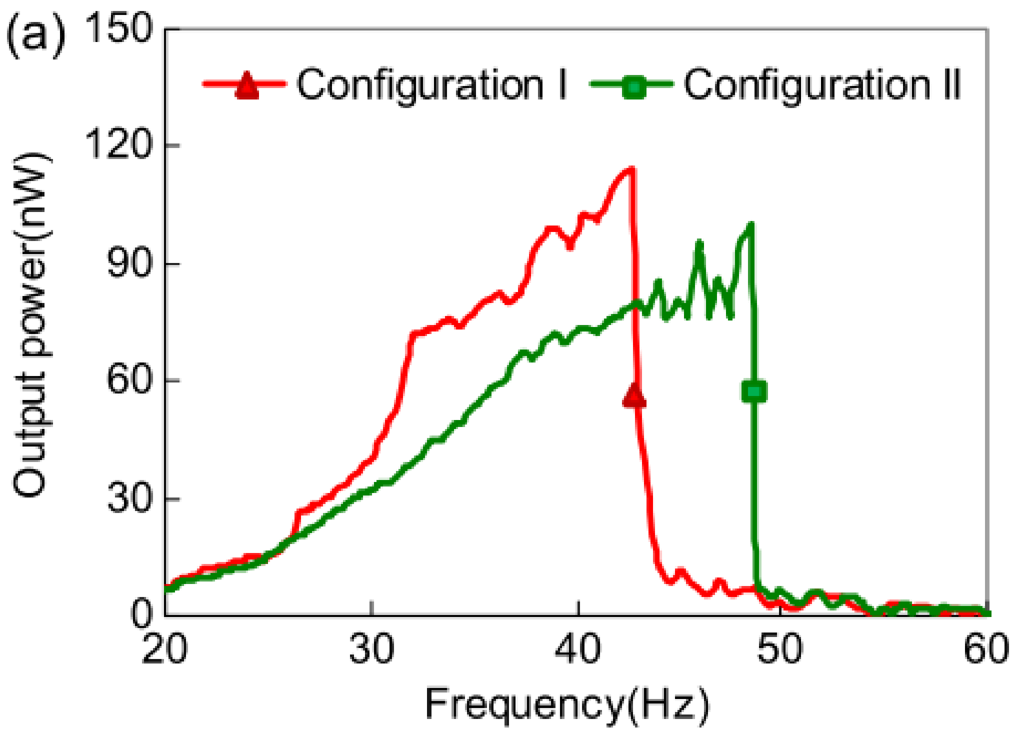

Figure 27: One side and two side stoppers output power [88]

5.4 Piezomagnetoelastic material

Piezomagnetoelastic materials have also been evaluated, which has also shown to be more beneficial in operating bandwidth compared to just piezoelastic material [89, 90]. At resonance the piezomagnetoelastic is only slightly lower compared to the piezoelastic counterpart however the bandwidth of the device using piezomagnetoelastic produces useful power output over 5-8 Hz [91].

5.5 Parametric Excitation

Parametric excitations are another class of nonlinear oscillators which can result in large motion amplitude occurring at twice the fundamental frequency of the system; this nonlinear behaviour is caused when the excitation is applied axially to the device. The literature for this type of energy harvester is rather limited compared to other methods in the existing literature. For instance, Abdelkefi et al. [92] theoretically investigated a parametrically excited cantilever beam for energy harvesting purposes using the Galerkin discretisation and the method of multiple scales; the modelling also includes geometric, inertial and piezoelectric nonlinearities. Daqaq et al. [93] investigated the applicability of parametric energy harvesting with large emphasis on the theoretical model using a perturbation technique; experiments were also conducted on a cantilevered beam with a tip mass—this system showed a weak softening-type nonlinearity in the vicinity of the principal parametric resonance.

5.6 Nonlinear extraction circuits

Another interface with useful potential increasing both harvested power and bandwidth of a vibration energy harvesting device is the addition of electrical components in the circuit itself. Even though there is mechanical damping losses it is assumed that the electrical damping ratio of the system is used as the electrical energy generated from the system. A circuit now gaining research interest in the field of vibration energy harvesters is Synchronized Switch Harvesting on Inductor (SSHI), which is used for switching the piezoelectric element in the circuit for short periods of time.

Modification of the electrical interface has numerous applications for macro micro and nano-scale devices, A nonlinear approach to optimise the synchronous electric charge extraction found that this principle was able to increase the harvested power by 400% which was backed by theoretical and experimental results [94].

The new SSHI circuit developed in [95] is able to increase the gain of the conventional system by 160% which is productive for all energy harvesting devices, this circuit is shown in Figure 28. This particular circuit is based on an approach proposed in [96].

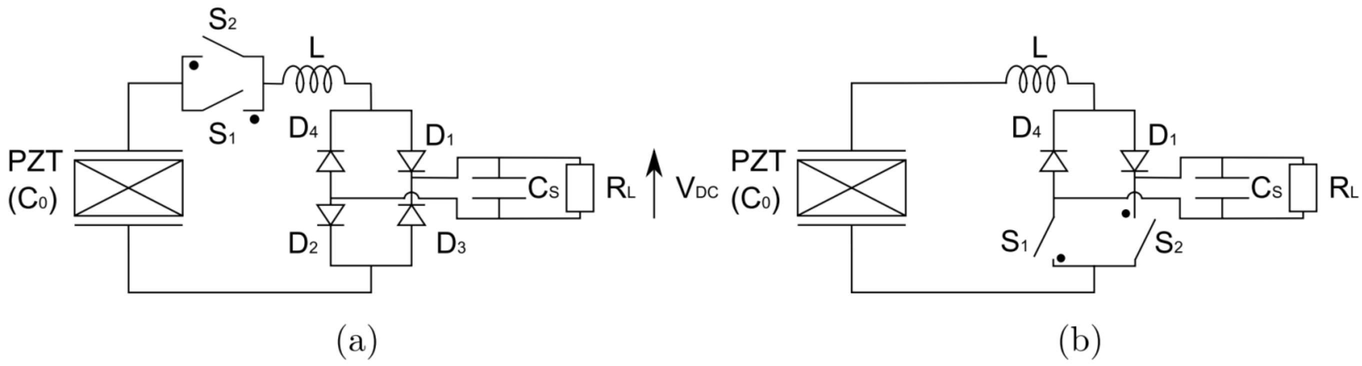

Figure 28: (a) Classical SSHI circuit (b) new SSHI circuit [95]

The SSHI circuit has also been thoroughly investigated using a new proposed method SSHI-MR which allows for a gain of 50 times compared to classical energy harvesters [97]. The author states "that it is very promising for energy harvesting at high mechanical frequencies, where displacements are very low but present high power capabilities".

A synchronised magnetic flux extraction circuit has also been shown to increase the operating range of a device, with larger bandwidths being produced for increasing vibration amplitude [98]. A rectified power output of 1.6 mW is harvested over a 10 Hz bandwidth for 1 g acceleration and 100 Hz excitation.

6 SUMMARY OF PERFORMANCE ENHANCEMENT TECHNIQUES

A summary of the techniques used for enhancing the performance of vibration based energy harvesters has been presented each with their own advantages and disadvantages this section is to summarise the various techniques accordingly.

Other researchers have also published their versions to classify the improvements in operating bandwidth for vibration energy harvesters [99-101]. Bi-stable energy harvesters also have the potential for nonlinearities to be effectively used for broadband ambient vibration energy harvesting [102, 103]. The scaling effects on output power for electromagnetic vibration energy harvesters has been investigated [104]. The differences in this paper compared to other existing literature are the categorising of power amplification techniques and frequency broadening techniques for the performance enhancement of (VBEH) devices, including new enhancement techniques that have not been previously mentioned.

The performance enhancement techniques reviewed here are of significant interest to the practical application of vibration energy harvesting devices whether gain amplification is applied through mechanical or electrical techniques or the effects of preload on a cantilever beam with a piezoelectric layer through to the effects of introducing nonlinear stiffness with the capabilities of bi-directional tuning.

6.1 Active versus Passive Tuning Methods

The question of whether active or passive tuning can be applied to increase the operating frequency of vibration energy harvesters. An investigation into tuneable devices through active methods has been investigated; active devices require a continuous power source in order to achieve tuning. Roundy states “that an active tuning actuator will never result in a net increase in power output” [105]. The tuned device resulted in an increase of output power (82 μW) however this was small compared to the power supplied to drive the tuning actuator (440 μW). As a result active tuning devices cannot supply more output power than the power required to tune the device which is not a feasible solution.

If active tuning can be achieved resulting in increased power output the effects of stochastic or randomly changing vibration spectra may not be able to be compensated with a controller due to fast changes occurring rapidly compared to the response time for tuning the device.

The techniques presented here have mostly been passive systems with altering stiffness change due to mechanical stress or induced magnetic stiffness. Further development into enhancing the performance of (VBEH) devices is essential for practical applications.

6.2 Comparison of Different Enhancement Techniques

This section compares the performance enhancement techniques presented based on their application, and enhanced performance capabilities. Table 2 evaluates the different performance enhancement techniques based upon the categories presented here highlighting the advantages and disadvantages of each technique accordingly.

The mechanical amplifier can increase the amplitude of vibration which is related to the maximum power output of the device which is particularly well suited for low frequency vibrations by applying gain to the system from the initial excitation but this also requires the device to compensate for the increased relative movement of the mass in the system. Frequency up conversion is well suited for low vibration frequency which the vibration frequency is amplified through various mechanisms; this is particularly suited for MEMS applications. Hybrid schemes show slight increase in operating frequency compared to single systems however the power output of such a design is improved using hybrid systems. The bandwidth is increased slightly for hybrid schemes; this will have to be coupled with other techniques to enhance the performance.

Multiple degrees of freedom on cantilever beams has been shown to create multiple resonance peaks which optimal parameter design needs to be selected for increasing the peaks amplitude while peaks are in close proximity to each other. Multimodal arrays have also shown potential based on arrays of individual cantilever beams with different beam dimensions, tip masses and natural frequencies; this design requires all the devices natural frequencies to be close to one another for effective operation however the electrical circuit of such a system becomes much more complex.

The mechanical tuning approaches have the ability to increase the bandwidth over larger ranges however during operation these devices are mostly passive systems and require changing preload or positioning for extensional mode. In operation this is not easy for tuning for random vibration spectra especially if the device is in remote areas. Magnetic tuning can also be used for increasing the bandwidth of the device usually this is done by applying magnetic interaction with different gap spacing to effectively change the natural frequency of the system due to an extra magnetic stiffness term.

Nonlinear stiffness techniques present a way of increasing the power output of a vibration energy harvester while increasing the operating range of the device. This has been done by the introduction of nonlinear magnetic stiffness through levitated magnet systems.

The bi-stable nonlinear system with deep potential well functions is much more applicable than the mono-stable counterpart as it is more suited for stochastic forcing which is realistic of actual operating conditions for the device. Both spring hardening and softening effects are ideal for a system and the potential of a bi-directional nonlinear stiffness is of great interest. Mechanical stoppers can be used to increase the operating frequency range of a device by passive means however more research into stochastic forcing needs to be conducted for this mechanism. The piezomagnetoelastic material was also shown to have broader vibration energy harvesting over the piezoelastic material which can also be utilised in devices. The electrical circuit interface also presents promise in amplifying the power and broadening the frequency range these devices include the (SSHI) circuit and magnetic flux extraction circuit however the complexity of these circuits are increased over traditional energy harvesters.

Table 2: Comparison of Performance Enhancement Techniques

Performance Enhancement Technique	**Class**	**Advantages Disadvantages**
Amplification		
	Mechanical Amplifier	• Increase the relative displacement of the mass • Increase power output • Broaden the operating frequency range • Need to consider extra space requirements for mechanism • Can work well in low frequency environmental vibrations
	Frequency Up Conversion	• Can work well in low frequency environmental vibrations • Well suited for MEMS devices
	Hybrid Systems	• Increased power output • Slightly broader operating frequency range • More complex circuitry required
Resonance Tuning		

	Multiple Degrees of Freedom	• Multiple resonance peaks with close proximity • Only works in vicinity of resonant peak
	Multimodal Arrays	• Broadened bandwidth • Increased power output • More complex circuitry required • Space considerations in design
	Preload	• Large increase in operating bandwidth • Complex to tune in practical applications
	Extensional mode	• Large increase in operating bandwidth • Complex to tune in practical applications
	Magnetic	• Complex to tune in practical applications • Increased operating bandwidth
	Complex Load Topology	• Increased operating bandwidth • Lower power output after tuning • Complex circuitry involved
Nonlinearities		
	Mono/Bistable	• More complex design for nonlinear system attributes • Increased operating bandwidth • Increase power output natural frequency is designed lower than that of the surrounding excitation • Deep potential well functions • Can increase with preload
	Stochastic Loading	• Can be used to improve nonlinear vibration energy harvester • Can amplify bistable harvester under certain dynamic loadings • Needs to be designed

	properly for effective use
Mechanical Stoppers	• Increased operating bandwidth • Loss of output power due to energy loss when contact is made with stoppers • Can prevent damage to piezoelectric elements due to shock forces
Piezomagnetoelastic	• Can have slight increase in operating bandwidth. • Power at resonance is lower than piezoelastic material • Can only be used piezoelectric conversion • Design must incorporate magnets
Extraction Circuits	• Can amplify power output of the harvesting device • More complex circuitry involved • Slight increase in operating bandwidth

7 CONCLUSION

With the limitations of conventional vibration based energy harvesters being the total available power output and narrow operating frequency range, these issues impact the efficiency of a device to produce useful output power.

The techniques presented in this review are current mechanisms that can produce more power from a (VBEH) device or increase the operating frequency range; while some techniques can achieve both of these requirements. These advances have been categorised into amplification techniques, resonance tuning mechanisms and nonlinear oscillations, these techniques are summarised below.

Amplification is the ability of a design to increase the relative displacement between mass and base, increasing the source vibration and combining two transduction mechanisms. Amplification is particularly well suited for improving the power output and operating range in low environmental excitations which is a key issue for all (VBEH) devices.

Resonance tuning mechanisms have been categorised by mass tuning, increasing the number of tip masses through to the use of multimodal arrays and stiffness tuning techniques have also been presented which contribute large effective operating bandwidths.

Nonlinear oscillators have the potential for both increasing power and the operating frequency range for a (VBEH) device, the bi-stable system can benefit from stochastic forcing which is expected of actual operating conditions.

Before (VBEH) devices can be used effectively in industrial and everyday life applications, this technology needs to be further developed to enhance the performance characteristics of these energy generators.

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