

A broadband vibration energy harvester with a soft magnetorheological elastomer-piezoelectric hybrid beam

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Abstract: Vibration energy harvesters have the ability to convert ambient kinetic energy into electrical energy; however, the problem of narrow bandwidth and small power generated is a prominent issue in this field. To achieve a broad frequency bandwidth, many techniques have been proposed and investigated, such as, multimodal, resonance tuning and non-linear techniques. This paper presents an innovative hybrid nonlinear vibration energy harvester consisting of a magnetorheological elastomer (MRE) layer, piezoelectric sheet and a tip mass. The newly proposed energy harvester makes use of the stiffness controllable characteristics of MRE to develop a nonlinear energy harvester. The multi-layered MRE-piezoelectric beam is enclosed by permanent magnets to close the magnetic circuit around the MRE and induce a nonlinear stiffness. The high flexibility of the soft magnetorheological elastomer-piezoelectric hybrid beam enables the energy harvester to have higher vibration amplitude compared to an equal thickness aluminium based harvester. Experimental and theoretical investigations have been performed to analyse the performance of the hybrid energy harvester, in particular, the effective bandwidth and generated power. Additionally, a linear energy harvester has been tested for comparison; furthermore, comparisons between the linear energy harvester and the hybrid energy harvester demonstrated that the hybrid nonlinear energy harvester has a wider effective frequency bandwidth and generates more power.

Key words: soft hybrid energy harvester; magnetorheological elastomer; piezoelectric; vibration; nonlinearity

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Power generation has become an increasingly important topic in modern society, largely due to the need for solving power shortage problems and reducing the world's dependency on fossil fuels. There are many sources of environmental energy that can be used for harvesting energy including solar^[1-2], wind^[3-4], geothermal^[5] and mechanical vibrations^[6-7]. Of these sources, the cheapest source of getting power is mechanical vibration, this is due to ambient kinetic energy being prevalent in everyday life^[8]. Vibration

energy has the advantages of long-lasting, cost saving, maintenance free and safer operating conditions. Vibration energy harvesting is widely used to produce power for small electronic devices^[9-11]. Vibration energy harvesters (VEHs) operate on the principle of a core element resonating in sync with the ambient vibration energy to generate power; however, this has a drawback in that, if the ambient excitation frequency shifts slightly the VEH produces little to no power. The problem of narrow bandwidth and small power generation is a key

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issue for VEH technology^[12].

For the mechanical methods, there are two types of tuning methods that can be used to solve the narrow bandwidth problem, these are manual tuning and self-tuning approaches. In manual tuning, the resonance frequency of the system can be tuned by changing the effective stiffness of the device by incorporating preload mechanisms. Leland et al^[13] used manual tuning of the natural frequency of the core element of a VEH by adjusting a screw based preload mechanism; either lowering or increasing with tensile or compressive load, respectively, the device had a broad operating frequency range of 200-250 Hz. Eichhorn et al^[14] also used a compressive axial load for manual tuning the effective stiffness of a cantilever beam with piezoelectric films; an enhanced operating bandwidth was generated by incorporating a preload. Youngsman et al^[15] developed an extensional mode resonator for manually tuning the stiffness of the piezoelectric sheets in plane tension of a piezoelectric sheet; the bandwidth of the device could be varied from 91 Hz to 95 Hz and the power generated from the piezoelectric layer varied from 1.53 mW to 1.95 mW, respectively.

Another method for increasing the effective operating bandwidth of a VEH is by utilizing the changing stiffness force in magnets, by applying a magnetic force to alter the effective stiffness of a VEH. The principle of this method uses attractive and repulsive forces between the magnets to produce variable stiffness behaviour. Challa et al^[16] theoretically and experimentally investigated a tunable VEH utilizing the linear variation of stiffness by adjusting the gap distance between a fixed magnet and a magnet on the resonating core element; an effective operating region of 10 Hz was generated using this type of tuning technique. Aboulfotouh et al^[17] also developed a linear magnetic tuning technique using two magnets and adjusting the gap between them for tuning; the effective operating bandwidth of the device was from 4.7-9.0 Hz. Mann et al^[18] developed a magnetic levitation based energy harvester utilizing the nonlinear stiffness attributes of

magnetic attraction and repulsion; the method of multiple time scales was used for the analytical method and the results agreed well with the experimental findings.

Other nonlinear technique for enhancing the broadband behaviour of VEH is by incorporating geometric nonlinearity; this type of nonlinear behaviour utilises the geometric configuration of the beam for broadband behaviour. For example, Abdelkefi et al^[19] theoretically investigated the power that could be harvested utilizing the nonlinear inertia and curvature of a cantilever beam; the model developed included geometric and piezoelectric nonlinearities. Another commonly used method for energy harvesting is to use mechanical stoppers in which a resonating cantilever beam contacts one or more mechanical stoppers; this method increases the bandwidth of the device, however, it reduces the power harvested^[20-23].

Another form of stiffness variable behaviour can arise in magnetorheological elastomers (MREs). MRE consists of micro-scale (3-5 μm) ferromagnetic particles, suspended in a non-magnetic solid or gel-like matrix^[24]. Due to their unique stiffness controllable and fast response properties^[25-26], MREs are ideal materials to develop advanced energy harvesters. However, little research has been done in this field except one preliminary work done by Sun et al^[27]. However, the proposed MRE energy harvester in their work requires extra power to control the stiffness of the MRE, which reduces the overall energy generated by the MRE harvester. Thus, designing a new structure employing MRE to avoid using extra power to control the stiffness of MRE can further improve the performance of an MRE energy harvester on its effective frequency bandwidth and energy harvesting capability. On the basis of this motivation, this paper proposes a new nonlinear MRE-piezo beam based energy harvester to obtain a wide bandwidth performance. The soft MRE-piezo cantilever beam has another advantage compared with an aluminium beam^[28-30] in that, this is large amplitude vibration which generates more energy

because the MRE is a soft rubber material. The detailed configuration of the energy harvester is shown in Section 2. Dynamic analysis, testing and modelling of the new energy harvester are shown in Section 3. Section 4 evaluates the energy harvesting of the energy harvester under harmonic and random excitations. Section 5 concludes this work.

1 Structure, prototype and working principle of the MRE energy harvester

Fig. 1 demonstrates the multi-layered cantilever beam which is made up of MRE and piezoelectric material. Permanent neodymium magnets are used for generating the magnetic field along the MRE introducing a nonlinear stiffness. The magnetic field across the beam is illustrated as green arrows in Fig. 1. The cantilever beam has a width of 10 mm, length of 100 mm and thickness of 5 mm and is made of four layers in total, i.e. two layers of MRE (with 2 mm thickness each) and two layers of piezoelectric material layers (with 0.5 mm

thickness each) in between MRE layers. The beam is surrounded by three permanent magnets denoted as P1, P2 and P3 (see Fig. 1). The length of the magnets P1 and P2 are both 110 mm which are parallel with each other, and the length of the P3 permanent magnet is 15 mm. In terms of the fabrication of the MRE energy harvester, the holders for the permanent magnets are printed using a 3D printer. The piezoelectric layers are bought from MFC company. The fabrication procedure of the MRE is detailed as follows: Three basic components; silicon rubber, iron particles and silicon oil are mixed to form a homogenous mixture. It is important that this mixture is free of contaminants such as air bubbles, which are removed by placing the mixture in a vacuum chamber. By performing these treatments, the MRE samples are much more likely to be uniform and have high permeability, both of which are influential on the final MR effect. After the mixing and treatment stages, curing of the samples is performed. The MRE samples are poured into a beam like mould for curing and after 5 days, the MRE is ready for use. The two piezoelectric beams are glued to each other and then the two MRE beams are glued to the two sides of the piezoelectric beam, separately.

Overall, the MRE layer of the hybrid beam is responsible for generating nonlinearity and the piezoelectric layer is designed to harvest the vibration energy to generate electrical power. Specifically, as the beam vibrates in the transverse direction, the beam will be exposed to a strong magnetic field as the beam passes the initial equilibrium position between magnets, and the magnetic field will decrease when the beam moves away from the magnet ring. As the stiffness of the MRE is sensitive to the magnetic field, the stiffness of the MRE beam will be harder when the beam is in between the magnet ring and softer when it passes away from the beam. Thus, a nonlinear stiffness is achieved and this complex nonlinear behaviour will lead to a larger effective frequency vibration bandwidth. The nonlinear vibration of the beam then will lead the piezoelectric layer to generate power. A secondary linear cantilever

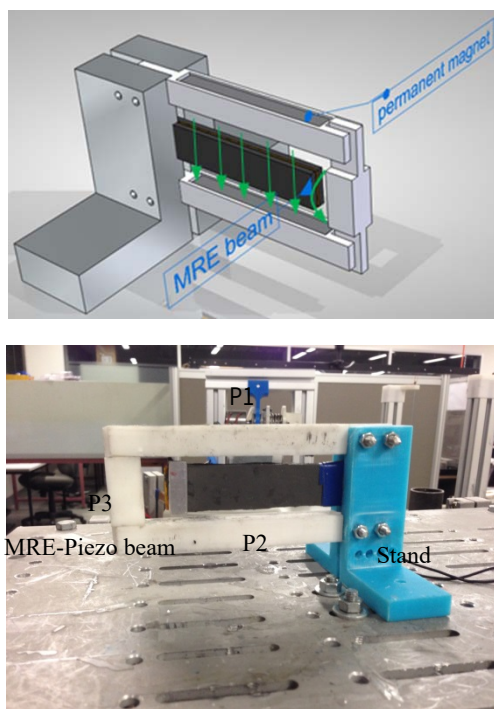


Fig. 1 Schematic and experimental photos of the proposed hybrid VEH

beam has also been fabricated for comparison. For the linear secondary cantilever beam, the MRE is replaced with a non-magnetic sensitive rubber beam and the rest design are the same. Without MRE materials, the secondary cantilever beam only performs linearly.

2 Testing and modelling the dynamic performance of the new energy harvester

2.1 Testing setup

An experimental flowchart of the setup used to test the proposed nonlinear-MRE VEH is shown in Fig. 2; the interaction of system components, measurement techniques and method for controlling the base acceleration are shown. The MRE energy harvester is excited using an electrodynamic shaker (VTS, V 100-8). A LABVIEW software program is used to perform sine input signals to the shaker for both forward and reverse frequency sweeps to excite the energy harvester. A power amplifier (Sinocera YE5871) is used to amplify the signal generated by the LABVIEW software to excite the energy harvester. An accelerometer (CAYD106) is connected to the electrodynamic shaker and a PID controller is implemented to control the excitation amplitude of the shaker at a constant acceleration during experiments; moreover, a sufficient settling time has been allowed to ensure that steady state data measurements are taken throughout all swept test

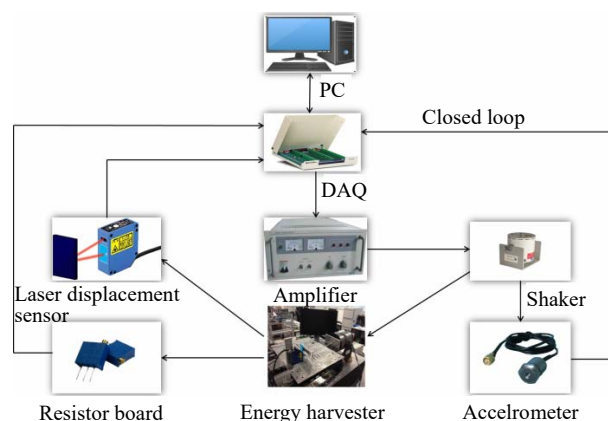


Fig. 2 Flow chart of the experimental setup and interaction of system components

frequencies. The displacement of the MRE beam is measured using a laser displacement sensor (NCDT1700IL1700-50) which measures the time domain vibration amplitude signal. The output voltage of the piezoelectric patch and the input frequency is evaluated through an NI CompactRio 9074 (NI 9229) and a data acquisition board (DAQ PCI-6221). A resistor board is also connected to the piezoelectric to vary the load and introduce a closed circuit for later experiments.

2.2 Dynamic response of the beam under harmonic excitation

A chirped sine signal with a frequency range from 5 Hz to 18 Hz, using 50 frequency testing points for the forward sweep excitation, and 18 Hz to 5 Hz for the reverse sweep excitation is programed into LABVIEW software to conduct the dynamic test. In the following experiments, the base acceleration is varied from $4 \text{ m}\cdot\text{s}^{-2}$ to $6 \text{ m}\cdot\text{s}^{-2}$ to excite both energy harvesters (i.e. with MRE beam and with non-magnetic beam).

The experimentally obtained frequency-response curves for the MRE-piezo VEH under various acceleration amplitudes are shown in Fig. 3. It was observed that with an acceleration of $6 \text{ m}\cdot\text{s}^{-2}$, the reverse sweep has larger displacement and wider frequency bandwidth than forward sweep testing; this is because the MRE-piezo VEH displayed a softening-type nonlinear behaviour with the frequency-response curves leaning towards the left. In addition, discontinuous jump up and down points were observed in the frequency domain. The nonlinear behaviour decreases as the

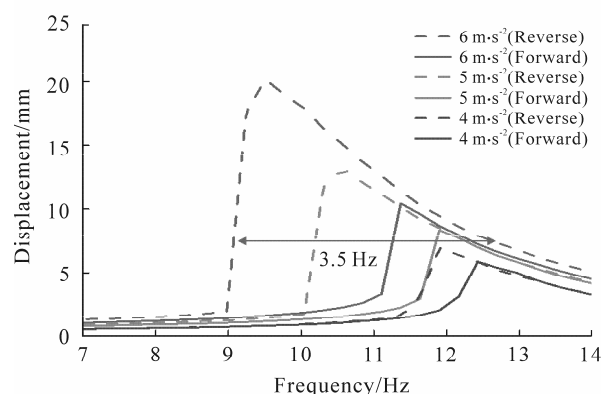


Fig. 3 Frequency-response curve of the MRE-piezo VEH

acceleration level decreased until a near linear response was observed for the system. For all acceleration levels the system showed softening-type behaviour; as the acceleration decreases, the effective frequency range and the amplitude decreased as well. Comparatively, the forward sweep has smaller displacement and narrower effective frequency range compared to the reverse sweep, which is a typical phenomenon for nonlinear beam. The maximum displacement for a base acceleration of $6 \text{ m}\cdot\text{s}^{-2}$ in the reverse direction was nearly 20 mm, which demonstrated the large deformation characteristics of the MRE-piezo VEH. These attributes indicate the high nonlinearity of the MRE-piezo VEH clearly and also demonstrate the wide broadband behaviour which is desirable for energy harvesting applications.

The linear VEH was also tested for comparison, the frequency-response curve has been experimentally obtained and plotted in Fig. 4. The performance of the energy harvester is linear because no discontinuous jump up and down points were observed compared to the MRE-piezo VEH.

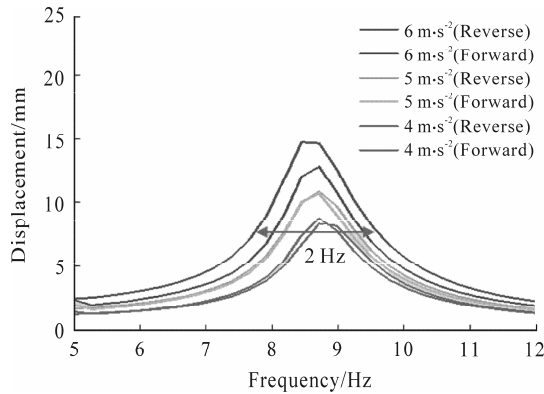


Fig. 4 Frequency-response curve of the linear beam

When comparing the frequency-response performance of the nonlinear and linear energy harvester, the comparison shows that the nonlinear behaviour has much larger bandwidth and higher vibration amplitude compared to the linear case, which is highly desirable behaviour for the energy harvesting device. Specifically, the performance of the two energy harvesters can be qualified by an example: their performance under the

reverse excitation with $6 \text{ m}\cdot\text{s}^{-2}$ amplitude. As shown in both Fig. 3 and Fig. 4, the frequency bandwidth of the nonlinear beam with response amplitude of 7.5 mm can reach 3.5 Hz while the linear beam can only reach 2 Hz. The maximum vibration amplitude of the nonlinear MRE energy harvester can reach 20 mm while the linear one only can achieve 15 mm under the same excitation.

2.3 Modelling of the nonlinearity of the MRE-piezo harvester

In order to provide a guideline for future MRE-piezo VEH design, in this section a numerical model using Matlab/Simulink is developed and validated by a comparison with the experimental results. The nonlinear MRE-piezo VEH can be modelled as a single degree of freedom (SDOF) lumped mass model incorporating a cubic nonlinear term for the nonlinear stiffness attribute from the magnetic interaction, shown as Eq. (1). This is a typical equation for describing nonlinear system.

$$m\ddot{x} + c(\dot{x}_1 - \dot{x}_0) + k_1(x_1 - x_0) + k_2(x_1 - x_0)^3 = 0, \quad (1)$$

where $m=28 \text{ g}$ is the effective mass of the beam, c is the damping of the beam, k_1 & k_2 are the linear and cubic stiffness of the beam respectively, x_1 & x_0 are the beam displacement and the excitation displacement, respectively.

In order to obtain the stiffness of the MRE-Piezo hybrid beam in Eq. (1), a testing system was built to test the force displacement relationship of it, as shown in Fig. 5. The frame of the VEH was fixed to a motor through a round platform. A force sensor (CA-YD-302) was mounted between a fixed pillar and the hybrid MRE-Piezo beam to measure the lateral force produced by the beam and a laser sensor (MICRO-EPSILON Company) was used to monitor the relative movement between the beam and magnet ring. The magnet ring of the VEH was forced to rotate by the motor. Then the relationship between the displacement and the force of the hybrid beam can be obtained. The parameters of the beam can be identified using the experimental results. The identified parameters are $k_1=251 \text{ N}\cdot\text{m}^{-1}$, $k_2=-500103 \text{ N}\cdot\text{m}^{-3}$ and $c=0.25 \text{ Ns}\cdot\text{m}^{-1}$. The comparison

between the simulation results using these parameters and the experimental results is presented in Fig. 6. The comparison result indicates the beam model can predict the performance of the hybrid beam well.

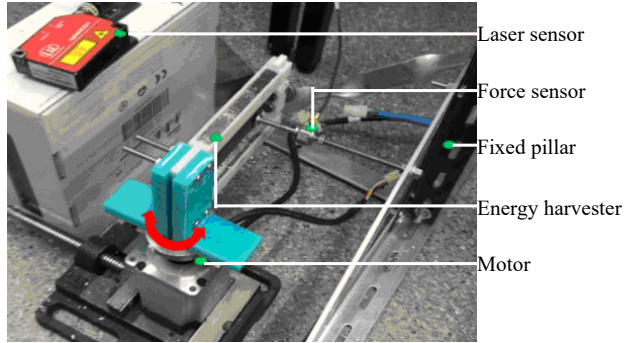


Fig. 5 Testing system for the beam property

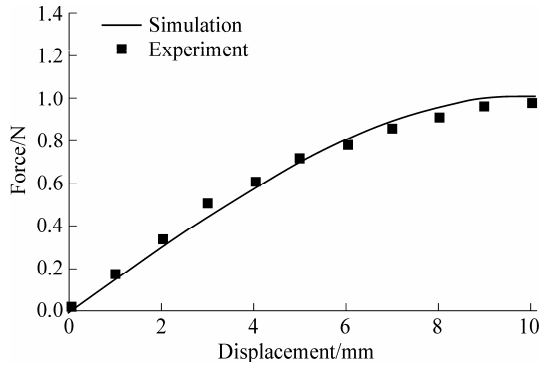


Fig. 6 Comparison between the simulation and experiment results

After the parameter identification of the beam, the beam model is complete and is simulated using a Runge-Kutta (RK) method which is already inbuilt in the MATLAB software. In this simulation the acceleration is set from $4 \text{ m}\cdot\text{s}^{-2}$ to $6 \text{ m}\cdot\text{s}^{-2}$. For the forward simulation, the frequency is set from 7 Hz to 14 Hz frequency while the reverse simulation sets the initial frequency as 14 Hz and final frequency as 7 Hz. The simulation results are illustrated in Fig. 7 and clear nonlinear bifurcation points were observed, which verified the nonlinearity of the energy harvester and correctness of the model. Moreover, comparing Fig. 7 and Fig. 3 (i.e. the numerical and experimental results), a good match between numerical and experimental results were obtained. This model can be used for designing new energy harvesters by predicting its dynamic performance.

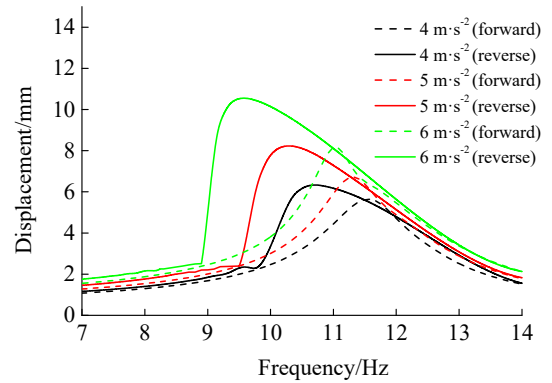


Fig. 7 Numerical simulation result of the nonlinear MRE-piezo VEH

3 The power generating capability of the energy harvester

The above section investigated the dynamic performance of the MRE-piezoelectric hybrid beam and verified the nonlinear behaviour of the MRE energy harvester compared to the linear VEH. This section measures voltage and power generated by the energy harvesters under both harmonic excitation and random excitation to evaluate its power generation capability and broadband behaviour.

3.1 The power generating capability of the energy harvester under harmonic excitation

For the first step, the voltage generated by the energy harvester with open loop circuit is measured and analysed. In the following tests, the test procedure is the same as with the displacement test, however, the voltage generated by the two piezoelectric sheet is measured individually with an NI CompactRio 9074 (NI 9229). The following results present the combined voltages from the two piezoelectric sheets. Fig. 8 shows the open-circuit frequency-voltage curve of the MRE-piezo VEH. Similarly, to the displacement curves, with growing base excitation the nonlinear behaviour increased. For a $6 \text{ m}\cdot\text{s}^{-2}$ base acceleration, the voltage generated was approximately 90 V due to the large amplitude vibration of the MRE-piezo VEH and the high strains induced in the piezoelectric sheets.

As a comparison, the energy harvesting performance

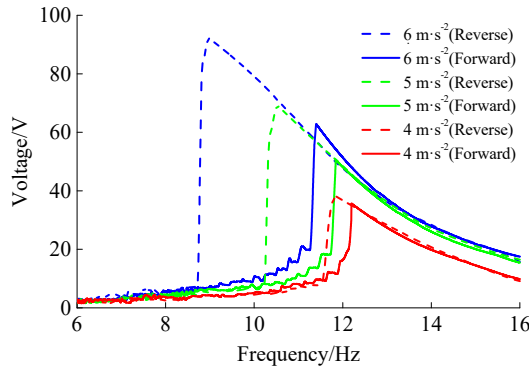


Fig. 8 Open-circuit frequency-voltage curve of the MRE-piezo VEH

of the linear energy harvester has also been experimentally tested, and the results are shown in Fig. 9. This shows that the minimum voltage produce is around 24 V and the maximum open circuit voltage is 44 V. The peak voltage produced under $6 \text{ m}\cdot\text{s}^{-2}$ excitation for both forward and reverse sweep was 40 V to 44 V, respectively. The comparison on the energy harvesting performance shows that nonlinear MRE-piezo energy harvester produces higher power than its linear counterpart. At a base acceleration amplitude of $6 \text{ m}\cdot\text{s}^{-2}$, the bandwidth of the MRE-piezo VEH is approximately 6 Hz larger than the linear beam; moreover, the MRE-piezo VEH has a maximum open circuit voltage of 90 V compared to the linear beam of 44 V, which was double the power produced by the linear VEH.

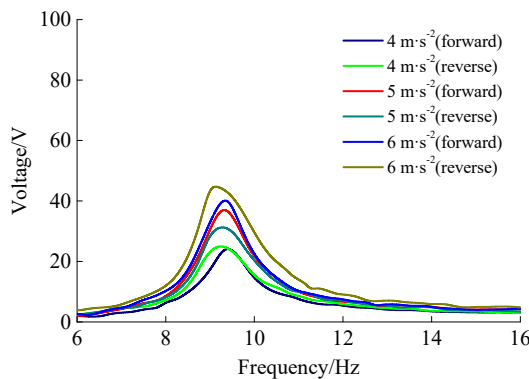


Fig. 9 Open-circuit frequency-voltage curve of the linear beam

As the second step to evaluate the power generating performance of the energy harvester, this section tested the performance of the nonlinear MRE-piezo energy harvester with a closed circuit loop

using a resistance board. The power generated by the piezoelectric strips is connected to different resistors ranging from $90 \text{ k}\Omega$ to $210 \text{ k}\Omega$. The energy harvester was tested with the same excitation as with the above sections.

The acceleration of the swept excitation is $5 \text{ m}\cdot\text{s}^{-2}$. This section tested the energy harvesting performance of the MRE beam with different resistance so as to find the optimal resistors for performance to achieve maximum power output.

Fig. 10 presents the experimentally obtained resistance-maximum power curves for the MRE-piezo VEH. It is shown that the energy harvester under reverse sweep generates more power compared to the forward sweep. The highest power output from the reverse sweep was around 1.1 mW with a $150 \text{ k}\Omega$ resistance; moreover, the highest power output of forward sweep was around 0.5 mW using the same resistance of $150 \text{ k}\Omega$.

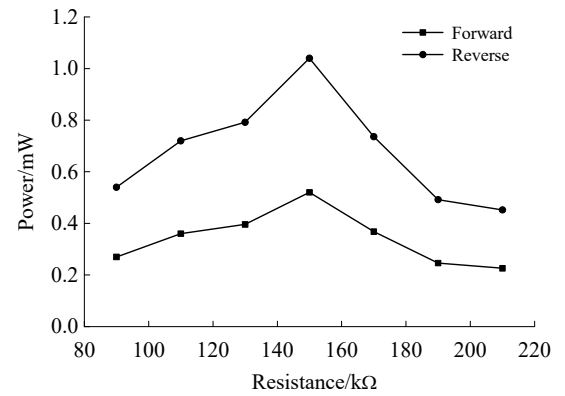


Fig. 10 Resistance-power curves for the MRE-piezo VEH

3.2 Power generation of the energy harvester under random excitation

In real applications, the majority of vibration energy sources are randomly scattered over various excitation frequencies. This section evaluates the energy harvesting performance of the MRE energy harvester under random excitation so as to find how much power output can be produced under a random excitation input. The acceleration spectrum of the random excitation is uniformly distributed from 0 Hz to 25 Hz, which covers all the frequency ranges for both the linear and nonlinear

MRE-piezo VEHs developed in this work. Fig. 11 shows the random excitation signal in the time domain, the RMS value of the excitation acceleration is set to $2 \text{ m}\cdot\text{s}^{-2}$.

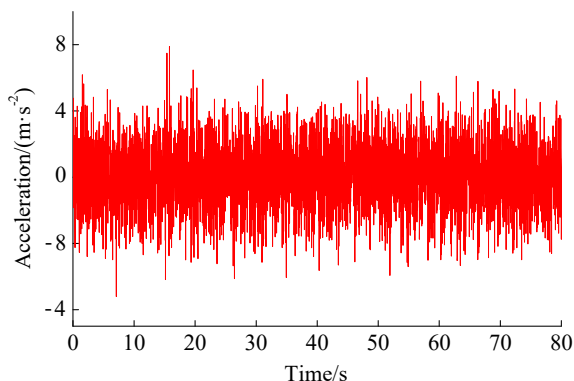


Fig. 11 Random excitation input in the time domain

The testing results of both linear and nonlinear MRE-piezo energy harvesters under random excitation inputs are presented in Fig. 12 and 13. The voltages were recorded through the NI CompactRio 9074 (NI 9229) using LABVIEW software. The generated voltages in the time domain by the two energy harvesters are presented in Fig. 12. It can be seen that nonlinear MRE-piezo energy harvester produced higher voltage compared to the linear energy harvester, this is due to the higher amplitude vibration of the MRE beam compared to the secondary linear beam.

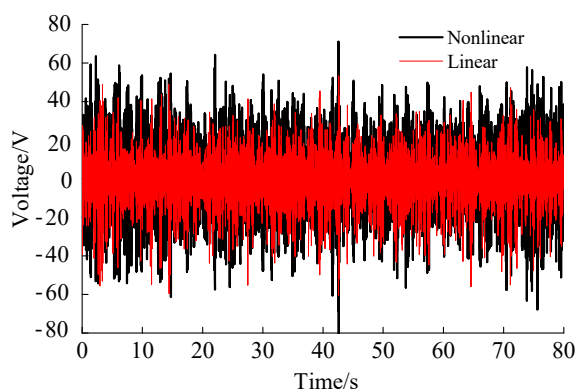


Fig. 12 Random excitation output voltage in the time domain

Fig. 13 shows the frequency domain of the output voltages from the Fast Fourier Transform (FFT) for both the linear and non-linear VEH, demonstrating the performance of the MRE-piezo VEH energy harvester

under random excitation in the frequency domain. According to this figure, the amplitude of the linear system is maximised between 9 Hz to 11.2 Hz with the highest amplitude of 320. Comparatively, the effective frequency bandwidth of the nonlinear MRE-piezo energy harvester is larger, which is between 11.7 Hz and 16.7 Hz and the maximum amplitude is much higher and reaches 400. In conclusion, it is observed that both magnitude and bandwidth are much higher for the nonlinear MRE energy harvester comparing to its linear counterpart.

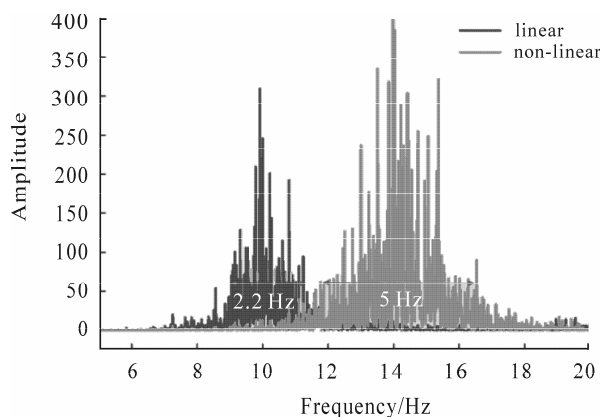


Fig. 13 Voltage output spectrum analysis of the random excitation

4 Conclusion

A new vibration energy harvester has been designed, fabricated and tested. Both simulation and experimental evaluation methods have been used to investigate the MRE-piezo VEH. The testing results indicate that a large nonlinear bandwidth was created due to the nonlinear stiffness attributes of the enclosed magnetic flux, stiffness controllability of the MRE material and the high vibrational amplitudes generated; it was also observed that the MRE-piezo VEH displayed strong softening-type nonlinearity with discontinuous jump up and down points in the frequency-space parameter. Moreover, this high vibrational nonlinear behaviour is highly desirable for energy harvesting characteristics. A model for the MRE-piezo VEH has been proposed to guide future MRE-piezo VEH design

and the simulation results using this model match well with experimental results. In summary, the investigation results verified that the nonlinear MRE-piezo energy harvester has broader effective frequency bandwidth and can generate higher power under the same excitation comparing with its linear counterpart.

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基于磁流变弹性体-压电片混合梁结构的宽频振动能量回收装置

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摘要: 振动能量回收装置能够将环境动能转化为电能, 然而其工作频率范围窄、产生的功率小是这个领域的突出问题. 为了增加其工作频率范围, 科研工作者已经开发研究了许多技术方案, 例如采用多种振动模式、谐振调谐和非线性技术来拓宽其有效频率范围. 本文提出了一种新型混合非线性振动能量回收装置, 主要包括磁流变弹性体(MRE)层、压电片和末端质量. 新提出的能量回收装置利用 MRE 的刚度可控特性来开发非线性能量回收装置. 多层 MRE 压电梁结构由永磁体包围, 以在 MRE 梁周围形成封闭磁场, 从而产生非线性刚度. 柔性磁流变弹性体-压电混合梁的高度柔韧性使得其与等厚度的铝基能量回收装置相比具有更大的振幅, 从而收集更多的能量. 同时, 对这一新型能量回收装置进行了实验和理论研究以分析其综合性能, 包括其有效工作频率范围和发电功率. 此外, 作为比较, 测试了一种线性能量采集器的各项性能. 线性能量采集器与混合能量采集器之间的比较表明, 本文所提出的混合非线性能量采集器具有更宽的有效频率范围, 并且能够回收更多的能量.

关键词: 软体混合能量回收装置; 磁流变弹性体; 压电; 振动; 非线性

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