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An impact-engaged two-degrees-of-freedom piezoelectric energy harvester for wideband operation

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Abstract

In order to achieve broadband energy harvesting, this paper proposes a two-degree-of-freedom piezoelectric energy harvesting system with stoppers. The synergy of the multi-modal technique and the nonlinearity feature benefits the wideband energy harvesting. First, the mechanism of the proposed system is described and the electromechanical model is developed. Subsequently, investigations of the effect of the presence of stoppers on the energy harvesting performance are carried out and compared to a linear 2-DOF counterpart. The impact-induced nonlinear dynamics is characterized by two parameters: the stopper distance and the stopper stiffness. A parametric study is performed to investigate the influence of these two parameters on the voltage output in terms of bandwidth and magnitude. Finally, to reconcile the demands of both operating bandwidth and the amplitude of output voltage, optimized stopper distance and stiffness have been recommended.

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Keywords: energy harvesting; impact; piecewise linear; piezoelectric

1. Introduction

Development of low-power microelectromechanical systems opens the possibility of directly employing energy harvesters as power supplies and getting rid of electrochemical batteries. Therefore, energy harvesting has attracted numerous research interests in recent years [1, 2]. Vibration energy harvesters scavenge energy from vibrations which exist ubiquitously in industries and our daily life. In order to have a robust performance, the operating bandwidth [3] and the conversion efficiency [4] (i.e., power output amplitude) are two main concerns in the design

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of vibration energy harvesters. Traditional linear vibration energy harvesters are only efficient near their resonant frequencies and quite sensitive to the variation of the external excitation [5]. Even a bit mis-match of the frequencies will lead to a significant deterioration of the energy harvesting performance and the power extracted in off-resonance conditions is actually too small for practical use.

Researchers have explored various ways to improve the energy harvesting performance in terms of the operating bandwidth. Kim et al. [6] designed a two degree-of-freedom (DOF) energy harvesting device that uses both the translational and rotational degrees of freedom. By tuning the system parameters, the two peaks in power response can get close and thus an increased operating bandwidth can be achieved. Tang and Yang [7] introduced a multi-DOF piezoelectric energy harvesting model. Through attaching some delicately tuned small oscillators to a 1-DOF energy harvester, multiple peaks in power response can be obtained with negligible sacrifice of power density. Aldraihem and Baz [4] enhanced the power output and increased the bandwidth simultaneously by connecting the conventional piezoelectric energy harvester to a dynamic magnifier. The mechanism of the increase of the operating bandwidth is actually the multi-modal technique: the proposed system has two degree-of-freedom, thus has two resonant frequencies that can contribute to the operating bandwidth. Based on the same idea, Zhou et al. [8] investigated a piezoelectric energy harvester with multi-modes. Both simulation and experimental results showed that the power output of the harvester can be magnified at multiple resonant frequencies. The aforementioned researches are all based on the multi-modal concept. Other researchers revealed the usefulness of nonlinearity to enhance wideband energy harvesting. Tang and Yang [9] proposed a nonlinear piezoelectric energy harvester by introducing a magnetic interaction between the energy harvesting beam and a magnetic oscillator. Both simulation and experimental results demonstrated the increase of the operating bandwidth of the nonlinear energy harvester. Liu et al. [10] increased the operating frequency bandwidth of the traditional 1-DOF piezoelectric energy harvester by introducing mechanical stoppers. Other investigations of impact-engaged nonlinear systems for the purpose of improving the energy harvesting performance are also reported in [11, 12].

In this paper, by combining the multi-modal technique [7] and the impact-engaged nonlinearity [10], a 2-DOF piezoelectric energy harvesting system with stoppers is proposed and explored. First, the mechanism of the proposed system is described and the governing equations of the proposed system are presented. Subsequently, through a parametric study, the frequency responses of the proposed system with different stopper distances and stopper stiffness are investigated and compared to those of its linear counterpart. Optimized stopper distances and stiffness are suggested to accommodate the requirements of both bandwidth and voltage amplitude.

2. Electromechanical model

For a linear energy harvesting system, even if the external excitation frequency shifts a bit from its resonant frequency, the response becomes significantly weakened. Impact-engaged energy harvesters have been proposed by many researchers [8, 11, 12]. Mechanical stoppers can induce impacts and introduce hardening nonlinear behavior extending its frequency response to the high frequency range beyond the linear resonance. In this paper, based on the impact-engaged energy harvester, the multi-modal technique is proposed to be synergized with the stopper for further enhancing the operating bandwidth. According to the research of Tang and Yang [7], two similar configurations of 2-DOF piezoelectric energy harvester are compared: in one configuration, the piezoelectric element is placed between the primary mass and the secondary mass (which is actually a minor extension of the model introduced in [4]); and in the other configuration, the piezoelectric element is placed between the primary mass and the base. They concluded that from the aspects of achieving two close resonant frequencies and high power density, placing the piezoelectric element between the primary mass and the base is a better design. Therefore, by combining the above two concepts, a 2-DOF piezoelectric energy harvester with stoppers is expected to be able to inherit the features of both close resonant peaks and the impact-engaged hardening dynamics for bandwidth widening. The proposed 2-DOF piezoelectric energy harvester with stoppers is shown in Fig. 1. It consists of a conventional 2-DOF system with stoppers installed on both sides of the primary mass; the piezoelectric transducer is placed between the base and the primary mass.

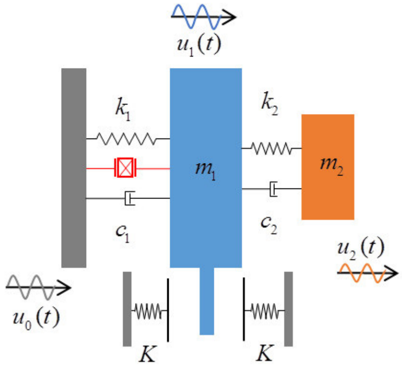

Fig. 1. Two-degree-of-freedom piezoelectric energy harvester with stoppers.

The governing equations of this model can be written as:

$$\begin{cases} m_1\ddot{x}_1 + c_1\dot{x}_1 + k(x_1) + g(x_1) + c_2(\dot{x}_1 - \dot{x}_2) + k_2(x_1 - x_2) + \theta v = -m_1\ddot{y} \\ m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = 0 \\ \dfrac{v}{R} + C^S\dot{v} - \theta\dot{x}_1 = 0 \end{cases} \tag{1}$$

in which m_1 and m_2 are the primary and the secondary masses; k_1 and k_2 are the stiffnesses of the suspension springs; c_1 and c_2 are the damping coefficients; θ is the electromechanical coupling coefficient; C^S is the clamped capacitance of the piezoelectric transducer; R is the load resistor connected to the piezoelectric transducer; v is the voltage across R. The restoring force $g(x_1)$ is a piecewise linear function that can be written as

$$g(x_1) = \begin{cases} K(x_1 + d) & (x_1 < -d) \\ 0 & (-d \le x_1 \le d) \\ K(x_1 - d) & (x_1 > d) \end{cases} \tag{2}$$

The piecewise linear spring stiffness emulates the impacting behavior of the primary mass: the change of the spring stiffness happens (as shown in Fig. 2) when impacts occur. For simplicity, the collisions between the primary mass and the stoppers are assumed to be completely elastic. The assumption of the conservation of kinetic energy during the impact process makes it reasonable to consider the impacting force as a restoring force and thus can take the form as Eq.(2) in which d denotes the stopper distance and K denotes the stopper stiffness.

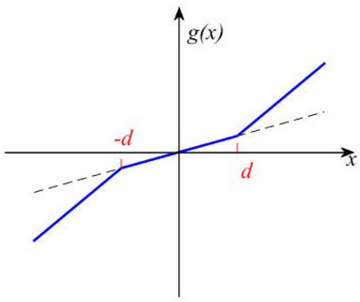

Fig. 2. Stiffness behavior of the piecewise linear system.

3. Energy harvesting performance

3.1. Energy harvesting performance of Linear 2-DOF piezoelectric energy harvester

The characteristics of a similar linear 2-DOF piezoelectric energy harvester without stoppers have already been fully revealed by the research of Tang and Yang [7]. They have conducted parametric studies to investigate the effects of various system parameters on the energy harvesting performance of the linear 2-DOF system and provided important design guidelines mainly in terms of tuning the mass ratio and the natural frequency ratio. The benefit of the linear 2-DOF system is that by connecting a small mass to the 1-DOF system through a spring, two close and enhanced peaks in power response can be achieved. As the small mass contributes only a slight increase of the overall weight, the power density of such configuration is improved comparing with the 1-DOF energy harvester without any attachment. Profiting from their work and based on their conclusions, we carefully selected a set of system parameters as shown in Table 1.

Table 1. Parameters of linear 2-DOF piezoelectric energy harvester.

Parameters	Values	Units
m_1	0.05	Kg
m_2	0.0022	Kg
k_1	150	N/m
k_2	6	N/m
c_1	0.1159	Ns/m
c_2	0.0046	Ns/m
θ	9.2e-05	N/V
C^S	180	nF
R	1e9	Ohm

Fig. 3 demonstrates the voltage output response for the linear counterpart (without stoppers) of our proposed system, under the excitation of $a_{RMS} = 0.5m/s^2$.

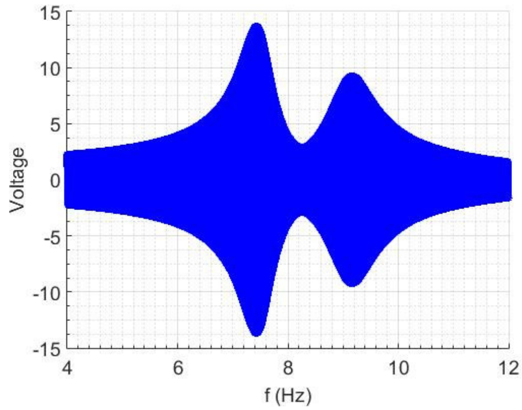

Fig. 3. Voltage frequency response of linear 2-DOF piezoelectric energy harvester.

In the following Section 3.2, focus will be on investigating the effects of the presence of stoppers on the energy harvesting performance.

3.2. Energy harvesting performance of 2-DOF piezoelectric energy harvester with stoppers

3.2.1. Effects of stopper distance

The stopper distance *d* plays an important role on the performance of the impact-engaged energy harvesting system. It can be easily speculated that if the stopper distance is too large, impacts will never happen between the primary mass and the stoppers and the system degenerates into its linear counterpart. While, if the stopper distance is tuned too small, the vibration of the primary mass will be significantly restricted and the vibration motion of the secondary mass which is directly connected to the primary mass is expected to be less violent, thus the energy harvesting performance will be worse than that of its linear counterpart. In order to facilitate the comparison between the system with stoppers and its linear counterpart, we use the same system parameters listed in Table 1 hereinafter. To investigate the frequency response of the system, we conduct frequency sweep under the excitation of $a_{RMS} = 0.5m/s^2$.

For a fixed stopper stiffness K ($K = 4k_1$), Fig. 4(a)-(d) depict the responses of the proposed system with different stopper distances. It is noted that the effective operating bandwidth has been significantly increased with the decrease of stopper distance *d*. It is also noted that the increase of the bandwidth is at the expense of the reduction of voltage amplitudes, especially for the first resonance. This can be easily observed by comparing Fig. 4(a), (b) and (c). In addition, by comparing Fig. 4 (c) and Fig. 3, we can note that though the amplitude of response around first resonance is decreased significantly, the bandwidth contributed from the second resonance is increased dramatically without sacrificing the amplitude, and in contrast, the amplitude of response around the second resonance is even increased. Overall speaking, we can conclude that the case corresponds to Fig. 4(b) has a better energy harvesting performance, a compromise between output amplitude and bandwidth. Then, we increase d a bit further. However, comparing the results presented in Fig. 4(d) and Fig. 3, it can be seen that the amplitude around the first resonance is decreased, and the amplitude around the second resonance is increased a bit but no obvious benefit in terms of bandwidth. In summary, in order to reconcile the demands of the bandwidth and the voltage amplitude, d = 12mm can be considered as the most preferable case.

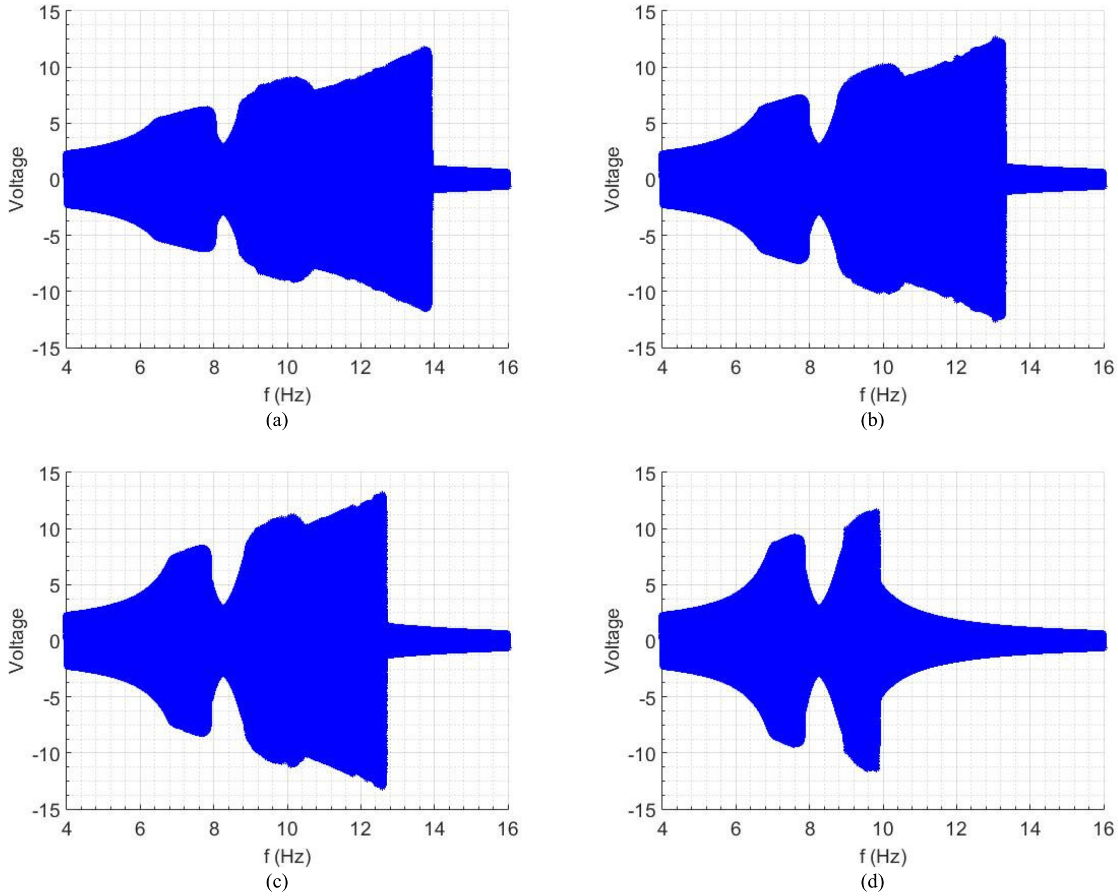

Fig. 4. Voltage frequency responses of 2-DOF piezoelectric energy harvester with stoppers (forward sweep): (a) d = 10mm; (b) d = 12mm; (c) d = 14mm; (d) d = 16mm.

3.2.2. Effects of stopper stiffness

The other important factor that affects the impacting behavior between the primary mass and the stoppers is the stopper stiffness K. In this section, the dimensionless parameter $\beta = K/k_1$ is used to describe the stopper stiffness.

For determined d = 12mm from Section 3.2.1, Fig. 5(a)-(d) present the responses of the proposed system for different β. It is noted that with the increase of β, the voltage amplitude decreases; the effective operating bandwidth first increases then decreases. From the perspective of an integrative consideration, a moderate β is recommended. The case of $\beta = 4$ shows a wide operating bandwidth without too much sacrifice of the voltage amplitude. In summary, $\beta = 4$ and d = 12mm are the preferred stopper parameters to reconcile the demands of both operating bandwidth and amplitude of the output voltage.

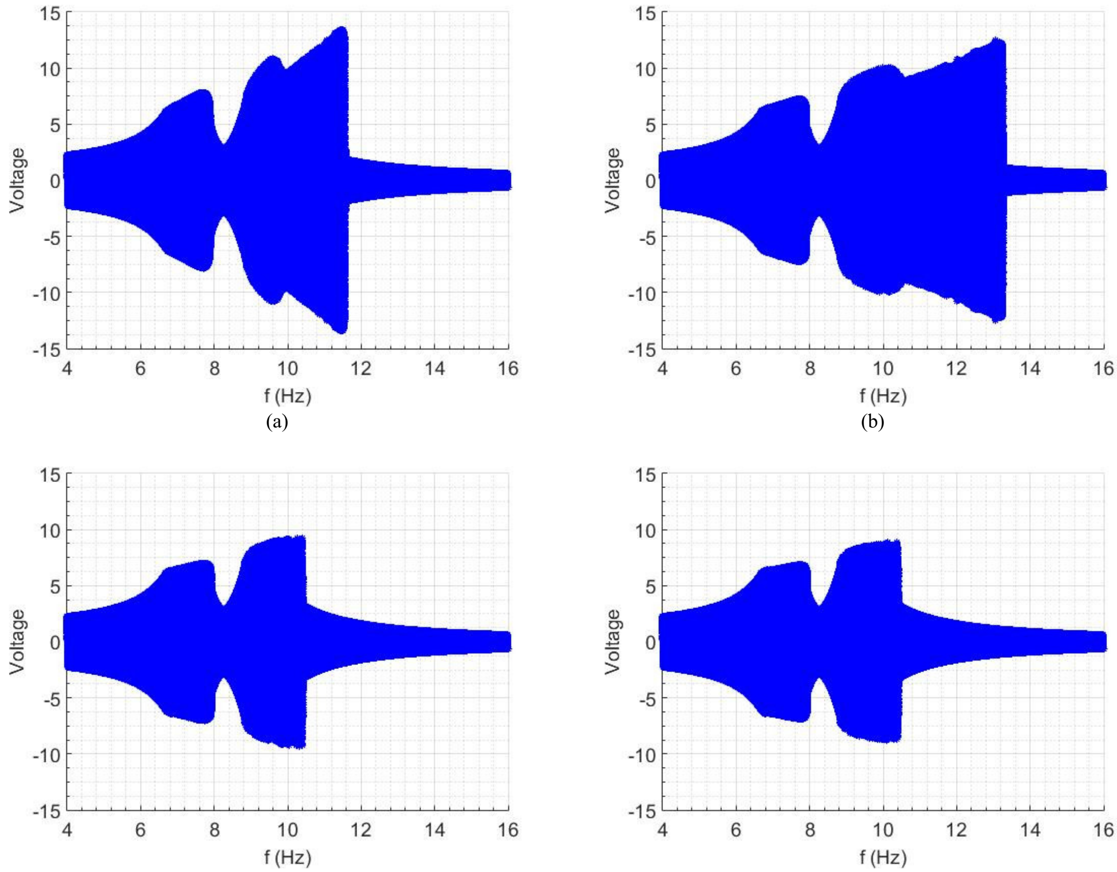

Fig. 5. Voltage frequency responses of 2-DOF piezoelectric energy harvester with stoppers (forward sweep): (a) β = 2; (b) β = 4; (c) β = 6; (d) β = 8.

4. Conclusions

This paper proposes and investigates a 2-DOF piezoelectric energy harvesting system with stoppers. In the development of the mathematical model of the system, the impacting behavior due to stoppers is emulated by using a piecewise linear stiffness function. According to numerical simulation, the proposed system shows a broadband energy harvesting performance as compared to its linear counterpart. However, it is found that the increase of the bandwidth is accompanied with the sacrifice of the voltage output amplitude. In order to reconcile the demands in terms of both operating bandwidth and output amplitude, optimized stopper distance and stiffness have been recommended after a parametric study.

References

1. Priya, S. and D.J. Inman, *Energy harvesting technologies*. Vol. 21. 2009, New York: Springer.
2. Kim, H.S., J.H. Kim, and J. Kim, *A Review of Piezoelectric Energy Harvesting Based on Vibration.* International Journal of Precision Engineering and Manufacturing, 2011. **12**(6): p. 1129-1141.

3. Zhu, D., M.J. Tudor, and S.P. Beeby, *Strategies for increasing the operating frequency range of vibration energy harvesters: a review.* Measurement Science and Technology, 2009. **21**(2): p. 022001.
4. Aldraihem, O. and A. Baz, *Energy harvester with a dynamic magnifier.* Journal of Intelligent Material Systems and Structures, 2011: p. 1045389X11402706.
5. Daqaq, M.F., R. Masana, A. Erturk, and D.D. Quinn, *On the Role of Nonlinearities in Vibratory Energy Harvesting: A Critical Review and Discussion.* Applied Mechanics Reviews, 2014. **66**(4): p. 040801.
6. Kim, I.-H., H.-J. Jung, B.M. Lee, and S.-J. Jang, *Broadband energy-harvesting using a two degree-of-freedom vibrating body.* Applied Physics Letters, 2011. **98**(21): p. 214102.
7. Tang, L.H. and Y.W. Yang, *A multiple-degree-of-freedom piezoelectric energy harvesting model.* Journal of Intelligent Material Systems and Structures, 2012. **23**(14): p. 1631-1647.
8. Zhou, W.L., G.R. Penamalli, and L. Zuo, *An efficient vibration energy harvester with a multi-mode dynamic magnifier.* Smart Materials and Structures, 2012. **21**(1).
9. Tang, L. and Y. Yang, *A nonlinear piezoelectric energy harvester with magnetic oscillator.* Applied Physics Letters, 2012. **101**(9): p. 094102.
10. Liu, H., C. Lee, T. Kobayashi, C.J. Tay, and C. Quan, *Investigation of a MEMS piezoelectric energy harvester system with a frequency-widened-bandwidth mechanism introduced by mechanical stoppers.* Smart Materials and Structures, 2012. **21**(3): p. 035005.
11. Kim, S., S. Ju, C. Ji, and S. Lee. *Equivalent circuit model of an impact-based piezoelectric energy harvester*. in *Journal of Physics: Conference Series*. 2014. p. 012094.
12. Soliman, M.S.M., E.M. Abdel-Rahman, E.F. El-Saadany, and R.R. Mansour, *A wideband vibration-based energy harvester.* Journal of Micromechanics and Microengineering, 2008. **18**(11): p. 115021.