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STAR-SHAPED ENERGY HARVESTING SYSTEM FOR MULTIDIRECTIONAL AND WIDEBAND EXCITATIONS

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Abstract. *Energy harvesting systems based on piezoelectric vibration devices have been developed for several applications and the main challenge is to enhance the device energy generation capacity. Ambient vibration excitations present multidirectional and broadband spectrum characteristics. In this regard, several research projects deal with the expansion of frequency bandwidth but the vibration direction effect on the harvester performance is usually neglected, treating excitations in the transversal direction. Piezoelectric energy harvesters (PEH) enhancement needs to consider multidirectional vibration energy in a broadband spectrum. In this work, a multimodal broadband PEH to extract energy from multidirectional excitations is investigated. The proposed harvester consists of a star-shaped structure composed of three L-shaped beams, six piezoelectric patches, and four pendular masses bonded to the main structure. The inertial pendular masses are used to harvest energy from multidirectional excitations in a wideband spectrum. Finite element analysis is developed using ANSYS. Simulations are carried out to design the system to operate in a desired operational frequency range and to evaluate the harvester performance. The proposed device is investigated under in-plane and out-of-plane excitations. Results show that the harvester presents performance advantages in terms of broadband spectrum and multidirectional sensitivity compared with conventional linear single-mode and unidirectional energy harvesters.*

Keywords: *Energy harvesting, multidirectional harvester, multimodal system, finite element analysis, piezoelectric*

1. INTRODUCTION

Piezoelectric energy harvesting has been used in the conversion of environment mechanical vibration energy into electric energy that can be useful for several purposes. Usually, vibration-based energy harvesting is related to the generation of small amount of energy, being used for recharging or replacing batteries in small and low-power electronic systems, and therefore, is a promising solution to portable self-powered electric devices. The most typical configuration employed in piezoelectric energy harvesters (PEH) is the piezoelectric beam device (Johnson *et al*., 2006; Sodano *et al*., 2004). Several works have been conducted investigating cantilever beam devices based on piezoelectric linear models (Erturk and Inman, 2009, 2008a, 2008b, 2008c). These devices present advantages such as simple structure, high-power-density, and better performance operating under resonant conditions. However, the system loses performance drastically when the excitation presents a broadband spectrum. This may limit the use of energy harvesters in applications where the ambient excitation presents wide frequency bandwidth and multi-directional sensitivity.

Different strategies can be employed to increase the performance of linear energy harvesters, including oscillator arrays, multi-modal and nonlinear systems (Tang *et al*., 2010; Zhu *et al*., 2009). Multiple-degrees-of-freedom (MDOF) systems are an interesting alternative to broader the frequency bandwidth of piezoelectric generators. These harvesters can be modeled as multiple degree-of-freedom oscillators or coupled oscillators with different natural frequencies designed with resonant peaks close enough to increase the operating frequency range (Caetano and Savi, 2021). Nonlinearities are another common strategy to improve the performance of linear generators. In this regard, nonlinear energy harvesters are mostly focused on impact systems, monostable, bistable, and tristable oscillator designs. Nonlinear harvesters present a broader resonant effect, widening the frequency bandwidth and improving the performance of the system by oscillating in high-amplitude orbits. Besides the advantages of MDOF and nonlinear harvester related to conventional cantilever-type generators, most of them operate under transverse vibration direction only been suitable for unidirectional vibration excitation.

In real-world applications such as human motion, wind, and ocean waves, ambient excitation comes from multiple directions and with a broadband frequency spectrum. A few PEH configurations have been investigated to extract energy from excitation with multiple directions. A mechanism that exploits the impact of a spiral cylindrical system with multi-piezoelectric beams is proposed by Yu *et al*. (2015) allowing the energy generation from three-directional excitations. Su and Zu (2013) employed magnetic interaction between magnets to couple three sub-systems providing a harvesting system capable of extracting energy from three directions with a wideband spectrum. Hung *et al*. (2015) utilized an inertial pendular mass coupled to four piezoelectric beams to convert energy from multiple directions.

In this work, a multidirectional star-shaped (MSS) device is designed and investigated aiming to extract energy from ambient vibration in a broadband spectrum. The system consists of a star-shaped substrate with six piezoelectric patches and four inertial pendular masses placed strategically in the substrate allowing energy extraction in three-axis directions. Finite element analysis is employed to analyze the system behavior using ANSYS software.

2. DESIGN CONCEPT AND MODELING

This section presents the design of the energy harvesting device in order to have multiple resonant peaks close enough to establish a broader frequency range and operate in three-axis directions. Figure 1 shows the proposed design composed of a substrate coupled with six piezoelectric patches and four inertial pendular masses. The substrate consists of three *L*-shaped beams arranged 120 degrees from each other and connected through one of its ends. Macro fiber composite (MFC) material is used for the piezoelectric patches and the pendular masses are made of steel alloy. Material properties of the harvester a provided in Table 1.

Table 1. Material properties of the energy harvester.

Parameter	Substrate	Piezoelectric	Tip Mass
Material	Aluminum	MFC0714-P2	Steel
Density (kg/m^3)	2700	5440	7850
Elastic modulus (GPa)	69	30.336	200
Poisson ratio	0.33	0.3	0.3
Length (mm) × width (mm) × thickness (mm)	68 × 8 × 1	7 × 14 × 0.3	–
Piezoelectric constant: e_{31} (C/m^2)	–	−5.16	–
Relative permittivity	–	1900	–
Permittivity constant (pF/m)	–	8.854	–
Modal damping ratio	0.02		

Figure 1 (b)-(d) shows the harvester subjected to in-plane and out-of-plane excitation. The idea is that *x*-axis excitation causes the pendular masses movement illustrated in Figure 1 (b). As a consequence, the pendular masses cause a deformation of the substrate generating electricity on the piezoelectric elements. For a *y*-axis excitation, similar behavior is observed as presented in Figure 1 (c). The pendular masses also experience inertial forces and moments when subjected to out-of-plane vibration, deflecting the structure which is converted into electricity as showed in Figure 1 (d). Therefore, energy harvesting is achieved by the proposed MSS device for in-plane and out-of-plane excitations.

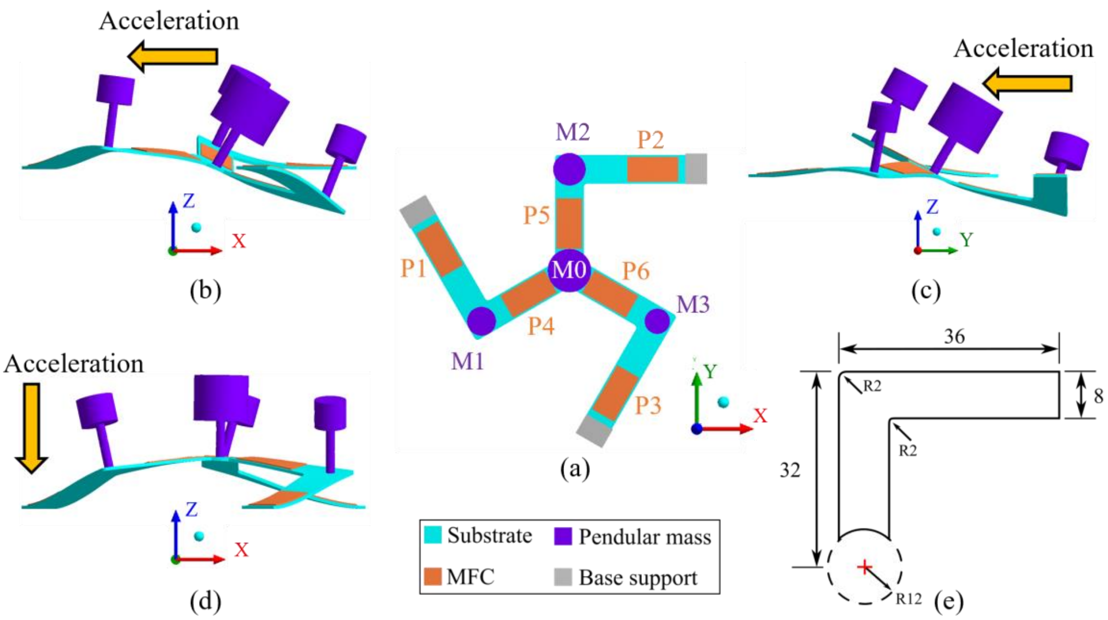

Figure 1. (a) Frontal view of the proposed MSS harvester; device state under acceleration in (b) *x*-axis, (c) *y*-axis and (d) *z*-axis directions; (e) schematic representation of one *L*-shaped leg with dimensions.

A typical configuration used to convert vibration to electrical energy is known as unimorph cantilever beam. This conventional energy harvester is shown in Figure 2, being considered as a base performance parameter. The system is composed of a two-layer sandwich structure with one piezoelectric material (MFC 2814-P2) bonded to a substrate elastic beam of dimensions: 60mm×14mm×1mm. A tip mass of 3.3 grams is placed at the beams' tip to adjust the resonant frequencies.

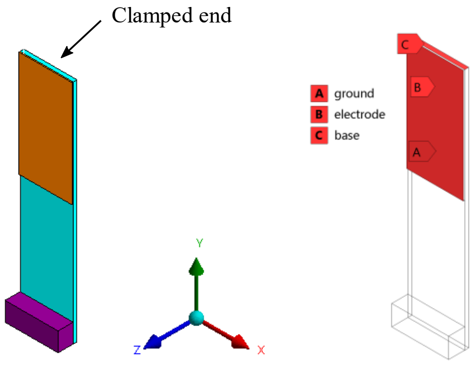

Figure 2. Cantilever-type energy harvesting device showing the boundary conditions.

Finite element analysis is employed to model the proposed MSS and the cantilever beam devices using ANSYS software. The SOLID186 and SOLID226 elements are used to model the substrate and piezoelectric patches, respectively. SOLID186 is a 20-nodes 3D structural element with three translational degrees-of-freedom per node in the *x*-, *y*- and *z*-directions. SOLID226 element presents an additional degree-of-freedom of electric potential for each node. The piezoelectric MFC material is utilized with the d_{31} sensing mode to convert bending strain into electric potential. The pendular masses are assumed as rigid bodies and modeled as point mass elements (MASS21) having three translational DOFs with properties defined in Table 2.

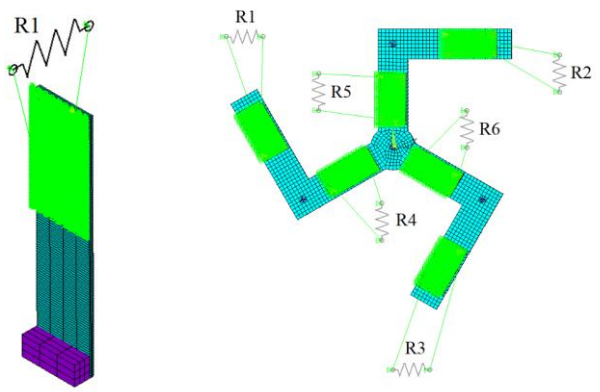

Figure 3. Electric circuit represented by a resistance load for the MSS and cantilever beam energy harvesters.

Table 2. Pendular masses properties.

	Mass (g)	Centroid coordinate (mm)	Moment of inertia (kg m^2)
M0	9.075	(0.0, 0.0, 12.8)	(1.693, 1.693, 1.583) × 10^{-7}
M1	2.614	(–24.20, –14.00, 0.122)	(0.327, 0.327, 0.188) × 10^{-7}
M2	3.243	(0.00, 28.00, 12.39)	(0.406, 0.406, 0.301) × 10^{-7}
M3	2.059	(24.25, –14.00, 12.04)	(0.268, 0.268, 0.111) × 10^{-7}

Piezoelectric elements have their electrodes emulated by coupling the voltage DOFs on the top and bottom surfaces to provide uniform electrical potentials as shown schematically in Figure 2 for the beam device. Additionally, a resistor element (CIRCU94) is coupled to the bottom and top electrodes for each piezoelectric material to provide a direct measurement of the output power. Therefore, the MSS model has six independent resistors, each one connected to one piezoelectric material while the beam model has one resistor element as shown in Figure 3. The ambient vibration is transferred to the harvesting system by a base support that is defined by coupling the nodes of each beam tip surface and applying displacement boundary conditions. Figure 2 shows a schematic representation of the applied boundary conditions for the cantilever beam model. Also, a dissipation mechanic is introduced in the analysis by considering a modal damping ratio of 2%.

The equation of motion for piezoelectric couple-field analysis can be written as follows:

$$\begin{bmatrix}[M] & [0]\\ [0] & [0]\end{bmatrix}\begin{Bmatrix}\{\ddot{u}\}\\ \{\ddot{V}\}\end{Bmatrix}+\begin{bmatrix}[C] & [0]\\ [0] & -[C^{vh}]\end{bmatrix}\begin{Bmatrix}\{\dot{u}\}\\ \{\dot{V}\}\end{Bmatrix}+\begin{bmatrix}[K] & [K^Z]\\ [K^Z]^T & -[K^d]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{V\}\end{Bmatrix}=\begin{Bmatrix}\{F\}\\ \{Q\}\end{Bmatrix}, \quad (1)$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices; $\{F\}$ is the vector of nodal surface forces; $[C^{vh}]$ and $[K^d]$ are the element dielectric damping and permittivity matrices; $\{Q\}$ is the vector of nodal charges, connected to material electric characteristics and $[K^d]$ is the piezoelectric coupling matrix.

Modal and harmonic analyses are performed to determine the performance of the system. Two performance metrics are considered: the frequency bandwidth and area under power density (PD) spectrum. The frequency bandwidth (δ) is obtained by applying the following relation, $PD(f_1) = PD(f_2) = 0.03PD_{max}$, where $\delta = f_2 - f_1$ and PD_{max} is the peak PD taken from the frequency response curve. The second metric provides a measurement of the total PD generated in the desired frequency range and it is calculated as follows:

$$A = \int_{\omega_0}^{\omega_f} PD(\omega)d\omega \quad (2)$$

where ω_0 and ω_f are lower and upper bound values that determine the frequency range of interest.

3. RESULTS AND DISCUSSIONS

This section deals with the performance investigation of the proposed MSS energy harvester device in terms of frequency bandwidth and multidirectional energy extraction. Initially, modal analysis is conducted to determine the natural frequencies and mode shapes of the system. Figure 4 shows the resonant frequencies and relative values of displacement distribution for the first six vibrational modes. Based on the displacement distribution, the first mode seems to be more interesting in terms of energy harvesting for out-of-plane excitations, while the second and third modes seem to be better for in-plane excitations, since higher deformation intensity is observed in the structure and, consequently, more electricity is converted by the piezoelectric materials. The other vibrational modes present areas with some level of deformation intensity, which could be explored to be converted into electricity, however lower intensity is spread in the piezoelectric areas.

Harmonic simulations are now carried out to obtain the system steady-state response for a frequency range of 70 – 550 Hz. Base support is subjected to an excitation of 1g (≈ 9.81 m/s^2) acceleration amplitude. The proposed device output power is obtained by adding the power generated in each resistor element. Once again, a conventional piezoelectric energy harvesting system is considered as a performance reference parameter to establish the advantages of the proposed configuration in terms of broadband frequency operation.

Figure 5(a) shows the system PD response for a system subjected to an out-of-plane vibration in the *z*-axis direction. The proposed device has the first mode as the predominant vibration mode, presenting a higher peak in terms of PD. The cantilever beam configuration provides higher values of frequency bandwidth (δ) and peak PD, characterized by a higher value of metric *A* when compared with the MSS device. By considering in-plane excitations (*x*-axis and *y*-axis directions), the PD spectrums are shown, respectively, in Figure 5(b) and Figure 5(c). The proposed MSS device presents performance advantages establishing several resonant peaks with higher values of PD, bandwidth (δ), and *A* metrics. For an excitation in the *x*-axis direction, the beam device does not generate energy as observed in Figure 5(b) since a torsional vibrational mode is excited and the piezoelectric material operates in the d_{31} bending mode. Finally, a combination of an in-plane and out-of-plane excitation is considered in the *x*-, *y*- and *z*-axis directions, resulting in the response spectrum given in Figure 5(d). Although the proposed MSS design presents performance improvements in terms of PD peaks for the multidirectional excitation, unavoidable valleys are observed among resonant peaks, defining regions that generated lower levels of energy with respect to the beam device. This results in similar values for the considered PD, δ and *A* metrics for the MSS design and the beam device. Therefore, the proposed MSS piezoelectric device shows potential to harness energy from a multidirectional vibration source in a broadband frequency spectrum, serving as an alternative to the unidirectional sensitivity limitation of conventional single-mode energy harvester devices. Future improvements are intended by designing the system to mitigate the valleys between resonant peaks to widen the frequency bandwidth, allowing energy extraction from vibration sources with broadband spectrum and multidirectional characteristics.

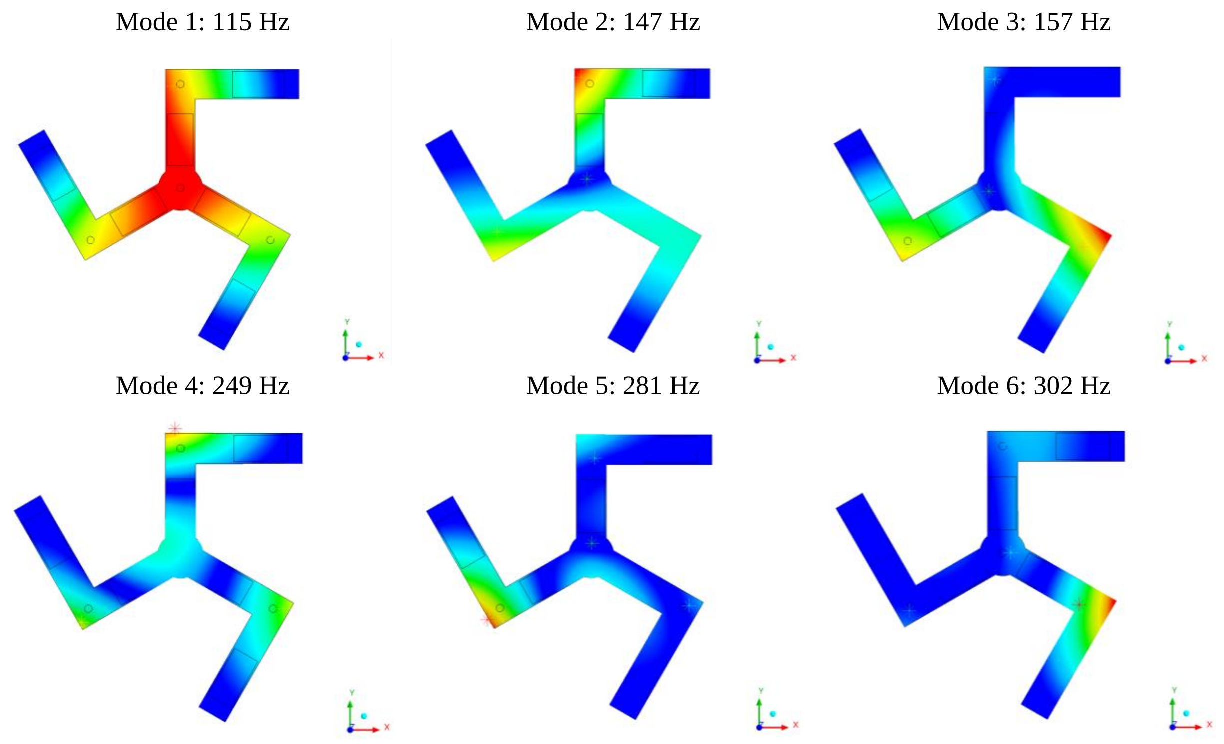

Figure 4. Natural frequencies of the MSS harvester and corresponding elastic strain distribution for six mode shapes.

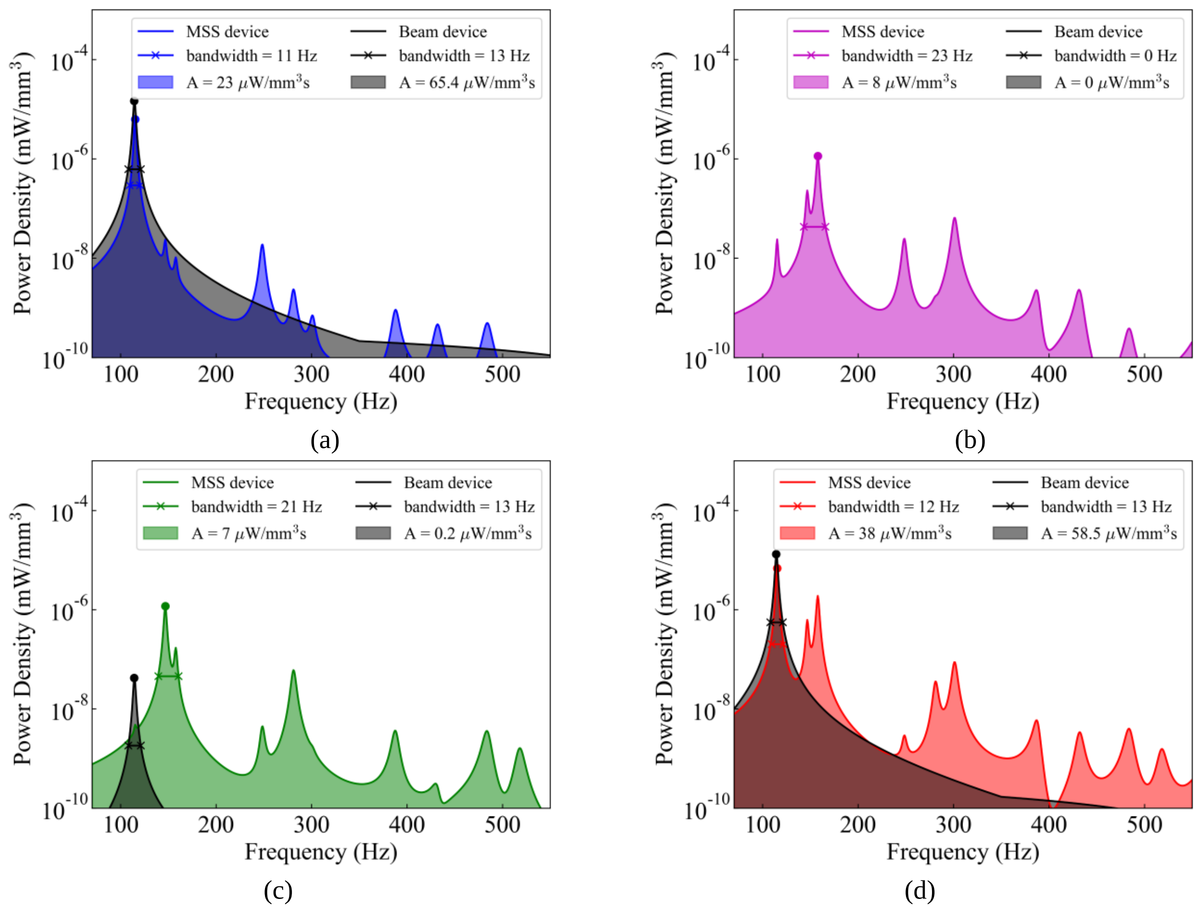

Figure 5. Proposed harvester output power spectrum under 1g amplitude excitation in (a) *z*-axis, (b) *x*-axis and (c) *y*-axis directions; (d) a combination of *x*-, *y*- and *z*-axis excitation; cantilever beam output power spectrum under 1g amplitude excitation in *z*-axis direction is provided for reference comparison.

4. CONCLUSIONS

This work proposed a multimodal star-shaped piezoelectric energy harvesting device to operate in a wideband frequency spectrum and from multidirectional vibration sources. The idea is to employ pendular masses to take advantage of inertia to extract ambient energy from multidirections. Finite element analysis is performed establishing modal and harmonic simulations. Results for in-plane and out-of-plane vibration show that the proposed device presents performance advantages in terms of power density, broadband frequency spectrum, and multidirectional excitation capability compared with conventional cantilever beam energy harvesters.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Caetano, V.J. and Savi, M.A., 2021. "Multimodal pizza-shaped piezoelectric vibration-based energy harvesters". *Journal of Intelligent Material Systems and Structures*.

Erturk, A., Inman, D.J., 2008a. "A Distributed Parameter Electromechanical Model for Cantilevered Piezoelectric Energy Harvesters". *Journal of Vibration and Acoustics*. Vol. 130, p. 041002.

Erturk, A., Inman, D.J., 2008b. "On Mechanical Modeling of Cantilevered Piezoelectric Vibration Energy Harvesters". *Journal of Intelligent Material System and Structures*. Vol. 19, p. 1311–1325.

Erturk, A., Inman, D.J., 2008c. "Issues in Mathematical Modeling of Piezoelectric Energy Harvesters". *Smart Material and Structures*. Vol. 17, p. 065016.

Erturk, A., Inman, D.J., 2009. "An Experimentally Validated Bimorph Cantilever Model for Piezoelectric Energy Harvesting from Base Excitations". *Smart Materials and Structures*. Vol. 18, p. 025009.

Hung, C.F., Chung, T.K., Yeh, P.C., Chen, C.C., Wang, C.M., Lin, S.H., 2015. "A Miniature Mechanical-Piezoelectric-Configured Three-Axis Vibrational Energy Harvester". *IEEE Sensors Journal*. Vol. 15, No. 10, p. 5601–5615.

Johnson, T.J., Charnegie, D., Clark, W.W., Buric, M., Kusic, G., 2006. *Energy harvesting from mechanical vibrations using piezoelectric cantilever beams. In: Smart Structures and Materials 2006: Damping and Isolation*., p. 61690D.

Sodano, H.A., Inman, D.J., Park, G., 2004. "A Review of Power Harvesting from Vibration using Piezoelectric Materials". *Shock and Vibration Digest*. Vol. 36, No. 3, p. 197–205.

Su, W.J., Zu, J., 2013. "An innovative tri-directional broadband piezoelectric energy harvester". Applied Physics Letters. Vol. 103, No. 20, p. 203901.

Tang, L., Yang, Y., Soh, C.K., 2010. "Toward Broadband Vibration-Based Energy Harvesting". *Journal of Intelligent Materials Systems and Structures*. Vol. 21, No. 18, p. 1867–1897.

Yu, Q., Yang, J., Yue, X., Yang, A., Zhao, J., Zhao, N., Wen, Y., Li, P., 2015. "3D, wideband vibro-impacting-based piezoelectric energy harvester". *AIP Advances*. Vol. 5, No. 4, p. 047144.

Zhu, D., Tudor, M.J., Beeby, S.P., 2009. "Strategies for Increasing the Operating Frequency Range of Vibration Energy Harvesters: A Review". *Measurement Science and Technology*. Vol. 21, No. 2, p. 022001.

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