



Performance Investigation of Mechanical Multimodal Energy Harvesting Designs for Multidirectional Excitations

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Abstract: *Energy harvesting from ambient mechanical vibration has been investigated as an alternative to power sources like batteries that have limitations due to periodic need of recharge and ultimately replacement. Ambient vibration excitations usually feature in a multidirectional and broadband frequency spectrum. In this regard, one of the main challenges is to develop devices capable of adapting to diverse sources of environmental excitation, being able to adapt and efficiently operate over a wideband spectrum. This work investigates multimodal and multidirectional designs of piezoelectric energy harvesting systems considering different ambient conditions. Different circular, pizza and star-shaped designs are proposed, comparing their performance with conventional cantilever-beam devices. The finite element method is employed to model system dynamics. An optimization procedure is applied to the system aiming to seek a configuration that can extract energy from multidirectional broadband frequency spectrum and maximize its output power. Modal, harmonic, and transient numerical simulations are carried out to investigate the harvester performances under multidirectional excitations. Results show that the proposed multimodal harvester designs have potential to harness energy from multidirectional wideband ambient vibration sources, serving as an alternative to conventional linear single-mode energy harvesters.*

Keywords: *Energy harvesting, Multimodal, Multidirectional, Piezoelectricity, Finite element analysis*

INTRODUCTION

The continuous evolution of electronic devices has been observed in recent decades toward the development of smaller, more robust and low-power consuming electronic systems. The energy harvesting concept has been considered as a promising solution to power portable autonomous electronic devices due to its low maintenance cost and sustainability. Especially nowadays with the movement toward the Internet of Things (IoT), with smart devices, sensors and wireless microelectronic, energy harvesting devices have been studied as an alternative to conventional power sources like batteries because of their limited lifetime and need for periodic recharging or replacement.

Energy harvesting is the process of generating electricity from harness energy available in the surrounding environment that, otherwise, would be wasted. Among several smart materials used as transducers mechanism, piezoelectric energy harvesters (PEH) have received most attention due to its simplicity, compatibility and high-power density. A typical linear energy harvester usually presents some limitations such as narrow operational bandwidth and unidirectional behavior, regardless of the structure and transduction materials (Erturk and Inman, 2008). Multimodal energy harvesters constitute an interesting alternative to increase the operational frequency range by establishing multiple resonant peaks, but also could be designed to operate under multidirectional excitations. Several works (Wang and Liao, 2017; Zhao et al., 2018; Suresh et al., 2019; Li et al., 2019) have developed devices that can efficiently generate more energy.

Although these devices are proven to extend the operational bandwidth, they still suffer from unidirectional sensitivity, usually being suitable for operating under transverse vibration direction. Little scientific effort (Hung et al., 2015; Su and Zu, 2013; Yu et al., 2015; Fattahi and Mirdamadi, 2020) have been carried out on PEH subjected to multidirectional and broad bandwidth excitations, such as ocean wave, wind and human motion. The proposed harvesters provide multidirectional sensitivity, however, the system presents narrow frequency bandwidth characterized by a single mode and losing performance for wideband excitations.

This work presents a comparative analysis between diverse multidirectional and multimodal piezoelectric mechanical energy harvesting systems showed in Fig. 1. The conventional cantilever beam is used as a base performance case. The devices are modeled using ANSYS finite-element software. Modal, harmonic, and transient analyses are carried out to determine the system response in the steady-state regime. Different performance metrics are utilized to establish suitable performance conditions for the harvesting devices under multidirectional ambient excitation, including output power, power density, frequency bandwidth and area under the power density spectrum curves.

DESIGN CONFIGURATIONS

The uni- and multidirectional multimodal piezoelectric mechanical energy harvesting designs investigated are showed in Fig. 1. These devices are composed of three main structures: substrate, piezoelectric patch, and proof mass. The substrate is assumed to be made of aluminum alloy. The macro fiber composite (MFC) material with d_{31} piezoelectric mode is used for harvesting energy from ambient vibration. Cylindrical tip masses are made of steel alloy and are used as a proper tuning mechanism of the resonant frequencies by carefully changing its weights. Besides the cylindrical masses, inertial pendular masses are also employed to extract energy from multidirectional vibration sources. Material properties of the harvester are presented in Tab. 1.

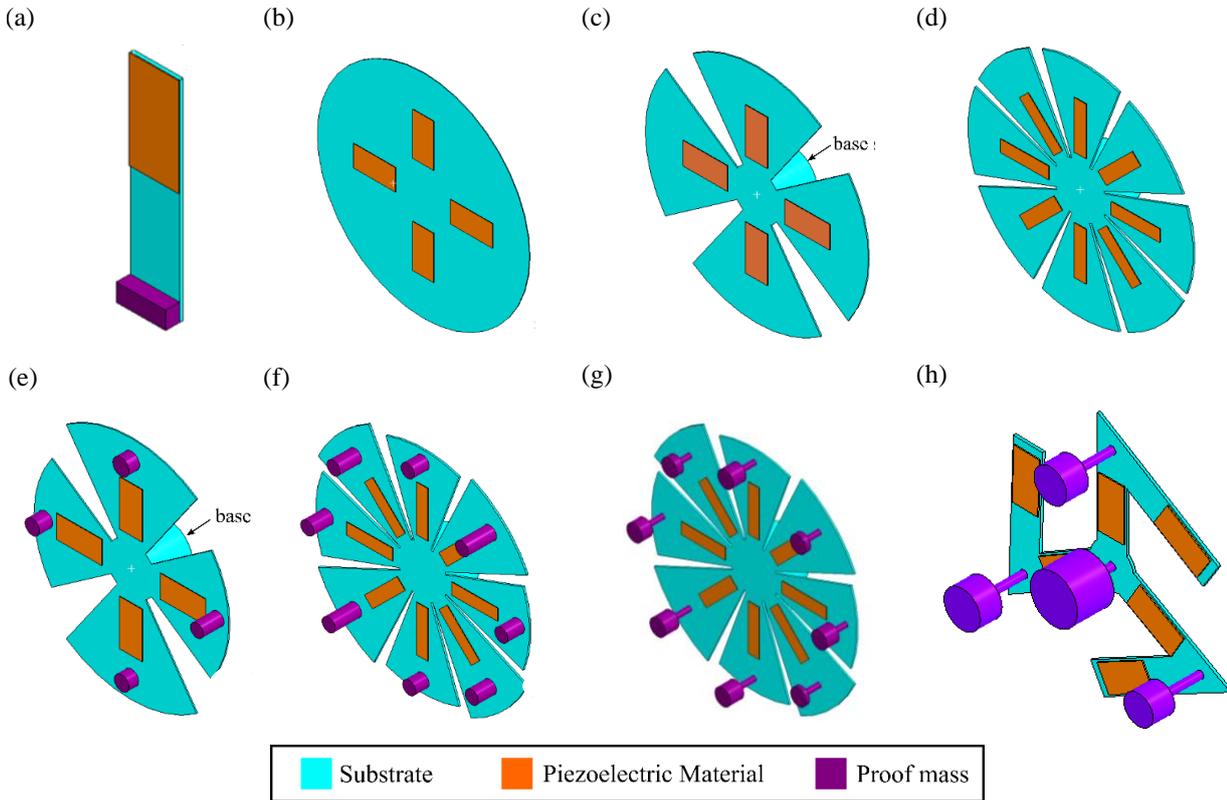


Figure 1 – Energy harvester configurations: a) cantilever beam, b) circular-shaped plate, (c) 4-slice pizza-shaped (4-SPS), (d) 8-slice pizza-shaped (8-SPS), (e) 4-irregular-slice pizza-shaped (4-ISPS), (f) 8-irregular-slice pizza-shaped (8-ISPS), (g) Multidirectional 8-irregular-slice pizza-shaped (8-ISPS-PM) and (h) Multidirectional Star-shaped (MSS) piezoelectric energy harvesters.

Table 1 – Material properties of energy harvesters.

Parameter	Substrate	Piezoelectric Materials	
Material	Aluminum	MFC2814	MFC2807
Density (kg/m ³)	2700	5440	5440
Elastic modulus (GPa)	69	30.336	30.336
Poisson ratio	0.33	0.3	0.3
Length (mm) × width (mm) × thickness (mm)	–	28 × 14 × 0.3	28 × 07 × 0.3
Piezoelectric constant (C/m ²)	–	–5.16	–5.16
Relative permittivity	–	1900	1900
Permittivity constant (pF/m)	–	8.854	8.854
Modal damping ratio	0.02	–	–

MATHEMATICAL FORMULATION AND OPTIMIZATION

A piezoelectric analysis involves bidirectional coupling between structural and electrical fields which are represented, respectively, by a displacement vector, $\{u\}$, and electrical potential, φ . Thus, in a tridimensional analysis, the system is described by four partial differential equations with four unknown variables, three mechanical displacements u_i , and one electric potential φ . After the application of the variational principle and finite element discretization (Allik, and Hughes, 1970), interpolation functions are used to express the continuous displacement and potential in terms of nodal values, resulting in the electromechanical equation of motion for a single element. Therefore, by performing a simple nodal addition of elemental contributions, the equation of motion for a linear structural system with piezoelectric coupling can be rewritten in a compact form.

$$[M]\{\ddot{\tilde{u}}\} + [C]\{\dot{\tilde{u}}\} + [K]\{\tilde{u}\} = \{F\} \quad (1)$$

where $[M]$, $[C]$ and $[K]$ are the global inertial, damping and stiffness matrices, respectively; $\{F\}$ is the global load vector; $\{\tilde{u}\}$ is the global nodal vector composed of the nodal displacement vector, $\{u\}$, and electrical potential vector, $\{\varphi\}$.

The energy harvesters are composed of three structures: substrate, piezoelectric patch and proof mass. ANSYS Workbench is employed for numerical simulations and three-dimensional structural elements are employed. Specifically, SOLID186 is employed to model the substrate that is a higher-order 20-nodes element that exhibits quadratic displacement behavior, having three translational degrees-of-freedom per node in the x -, y - and z -directions. Element SOLID226 is employed to model the piezoelectric patches, being similar to the previous one but presenting an additional degree-of-freedom of electric potential for each node. The piezoelectric material uses the d_{31} sensing mode to convert bending strain into electric potential. The harvester configurations have the proof masses assumed to be rigid bodies and modeled as point mass elements (MASS21). The electronic circuit is represented by an electric load resistance using element CIRC94. Three types of analyses, including modal, harmonic and transient, are employed to either analyze and investigate energy harvester devices.

The performance of the energy harvesters is evaluated considering the frequency bandwidth (δ) and the area under the power density curve (A). The power density (PD) is defined as the generated output power over unit of piezoelectric volume. The frequency bandwidth (δ) is estimated by applying the following relation, $PD(\omega_1) = PD(\omega_2) = 0.02PD_{max}$, where $\delta = \omega_2 - \omega_1$ and PD_{max} is the peak power density taken from the frequency response curve. The performance metric A provides a measure of the generated power density within the operational frequency range defined by $A = \int_{\omega_1}^{\omega_2} PD(\omega) d\omega$.

This work considers an optimization procedure based on the idea of extracting energy from a wideband ambient vibration excitation from a piezoelectric energy harvesting device. The main objective is the design of the energy harvester to optimize a multimodal device aiming to set as many resonant frequencies as possible in a desired operational frequency range. The optimization procedure is performed by setting some geometric parameters, defined a priori, in such a way that maximizes the number of modes laying in the required interval. The optimization is performed considering a frequency range defined by a lower limit, ω_L , and an upper limit, ω_U , containing p resonant frequencies in it. By considering that ω_i ($i = 1, \dots, p$) is a generic frequency within this interval, it is possible to define the optimization problem

$$\begin{aligned} & \min_{\omega} f_j(\omega) \\ & \text{subject to } g_n^\omega \leq 0 \text{ and } g_k^M \leq 0 \end{aligned} \quad (2)$$

The objective functions f_j ($j = 1, \dots, p + 1$) are based on frequency determination as follows:

$$\begin{aligned} f_1 &= \omega_1 - \omega_L \\ f_n &= \omega_n - \omega_{n-1} \quad (n = 2, \dots, p - 1) \\ f_p &= \omega_p - \omega_U \\ f_{p+1} &= -A \end{aligned} \quad (3)$$

Note that the last objective function is related to the area under the PSD frequency spectrum that needs to be maximized and the optimization is constructed as a minimization problem. This is the reason for the minus signal for the objective function f_{p+1} . Additionally, the constraints are defined considering a minimal value of variation from consecutive frequencies, ω_g , and a maximum value of the weight of each tip mass, M_U .

The optimization procedure is built by establishing mechanical and geometric parameters to tune the resonant frequencies aiming at a wider frequency bandwidth. Resonant frequencies are written as a function of mechanical and geometric parameters. The design optimization space is defined by lower and upper bound values for each one of these parameters, which are imposed based on physical and geometric restrictions. The optimization procedure uses a Goal-Driven Optimization (GDO) method, achieved using ANSYS, which is a deterministic method based on Design of Experiments (DOE), Response Surface (RS) and Optimization. The DOE is used to determine sampling points (design points) within the desired design space where the output parameters are represented in terms of input parameters.

Response surfaces are built from the DOE data and provide the approximated values of output parameters in the design domain by fitting surface curves. A constrained, multi-objective optimization technique is employed to obtain the best possible designs from a sample set given the objectives or constraints. The *Screening* method is adopted since it is a good approach to establish the most suitable candidate points in preliminary design, presenting relatively low computation cost.

Since a multi-objective problem is solved, the solution is given by a Pareto’s frontier curve, in which various solutions exist that optimizes the system according to the objectives and restrictions. The decision process to determine the most suitable Pareto solution from a sample set is based on a single, weighted objective cost function given by:

$$\phi \equiv \sum_{i=1}^n w_i G_i + \sum_{j=1}^m w_j Q_j \tag{4}$$

where n is the number of input parameters while m is the number of output parameters; $G_i = (|x_t - x|)/(x_U - x_L)$ are normalized objectives for input parameters; $Q_j = (|y_t - y|)/(y_U - y_L)$ are normalized objectives for output parameters; w_i is the weights. Therefore, the population of design points can be sorted in ascending order of ϕ to establish the best candidate points.

RESULTS AND DISCUSSION

Harmonic analyses are performed to obtain the steady-state system response for a frequency range from 70 to 200 Hz. A comparative analysis of the generated output power spectrum is shown in Fig. 2. Based on the results, it is noticeable that multimodal designs present a broader spectrum with the 8-ISPS device achieving wider bandwidth compared to conventional energy harvesters. The resonant peaks are designed to be spread enough to extend the frequency bandwidth but also sufficiently close in such a way that the valleys among them are mitigated. This is an interesting advantage.

In Fig. 3 is provided a quantitative comparative analysis regarding the frequency bandwidth (δ) and the performance metric A for unidirectional excitation in the z -axis (I), x -axis (II), y -axis (III) and multidirectional excitations conditions (IV-VI). Results show that the conventional cantilever beam presents good performance only for transversal (z -axis) excitation having higher peak of PD but lower values of frequency bandwidth (δ) which provides lower values of parameter A compared with the pizza-shaped devices. The pizza-shaped configurations are more interesting for applications where the excitation presents a wideband spectrum. The 8-ISPS-PM configuration provides more versatility to explore all potential energy available from the multidirectional ambient vibration sources with broadband frequency spectrum.

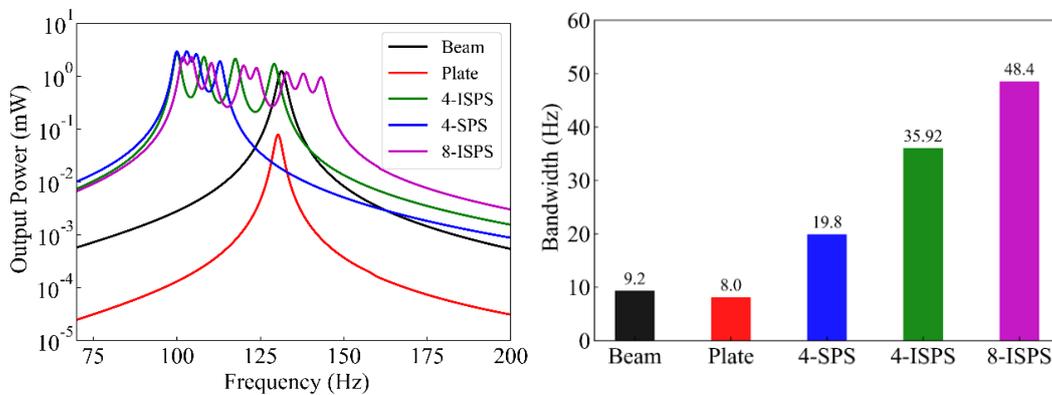


Figure 2 – Comparative of output power frequency spectrum curves and (b) frequency bandwidth of all five EH configurations under 1.0g base acceleration.

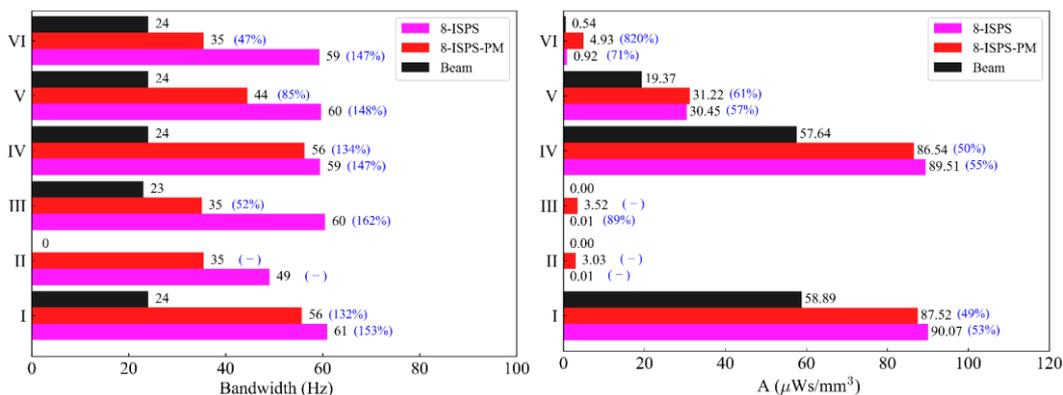


Figure 3 – Comparative analysis of (a) frequency bandwidth and (b) performance metric A for the cantilever beam, 8-ISPS and 8-ISPS-PM devices under different excitation conditions.

Subsequently, a similar quantitative comparative analysis is provided for the star-shaped harvesters with results summarized in Fig. 4. The MSS device presents higher values of parameter A for excitation in multiple directions. For an out-of-plane (z -axis) excitation, the multidirectional capability of the MSS device causes an increase of the frequency bandwidth by designing the multimodal system to have close resonant peaks. This constitutes an advantage in terms of energy extraction from broadband frequency spectrum. Therefore, the proposed MSS device allows the exploration of more energy available from ambient excitations providing an interesting alternative to single-mode and unidirectional energy harvesting systems. In conclusion, this work presented a comparative analysis between different multimodal piezoelectric mechanical energy harvesting devices designed to operate in a wideband frequency spectrum and from multidirectional vibration sources. Results show the performance in terms of power density, broadband frequency spectrum and multidirectional excitation capability, being able to explore all potential energy available from the environment excitation source.

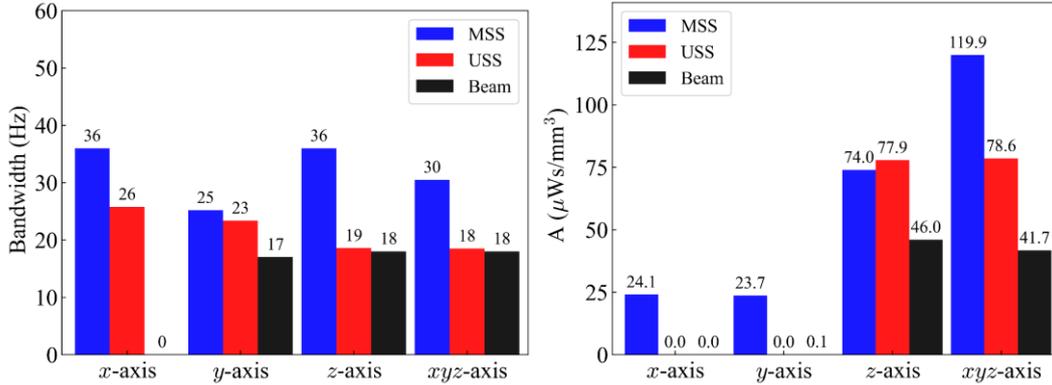


Figure 4 – Comparative analysis of (a) frequency bandwidth (δ) and (b) area under PD curve (A) between the optimized MSS, USS, and cantilever-beam devices.

Ambient vibration sources have uncertainties in the majority of engineering applications usually related with multidirectional vibration with their energy distributed over wideband spectrum. In this regard, the energy harvester configurations are now investigated considering nondeterministic excitations testing their performance through different vibration source conditions. The system is subjected to harmonic base excitation, defined as $u_b(t) = u_0 \sin(\Omega t)$ where the fluctuations are represented by a random-frequency spectrum $\Omega = N(\bar{\Omega}, \sigma)$ that corresponds to a Gaussian white noise with a mean value $\bar{\Omega} = 130$ Hz and standard-deviation $\sigma = 4$ Hz. A time-history signal divided into three regions is built to investigate the multidirectional characteristics of the proposed harvester designs. In the first region, a z -axis out-of-plane excitation is considered. Afterward, the second region considers in-plane excitation is assumed simultaneously in the x - and y -axis directions. Finally, a multidirectional excitation is considered in the third region, assuming a combination of in-plane and out-of-plane excitations (x -, y - and z -axis directions). The multidirectional time-history signal for the random-frequency base excitation is constructed considering: $u_x = \alpha_x u_0$, $u_y = \alpha_y u_0$ and $u_z = \alpha_z u_0$. The same energy input is provided to the harvester by respecting the following relation: $u_0 = \sqrt{u_x^2 + u_y^2 + u_z^2}$ for multidirectional excitation with $u_0 = 14.48 \mu m$ displacement amplitude.

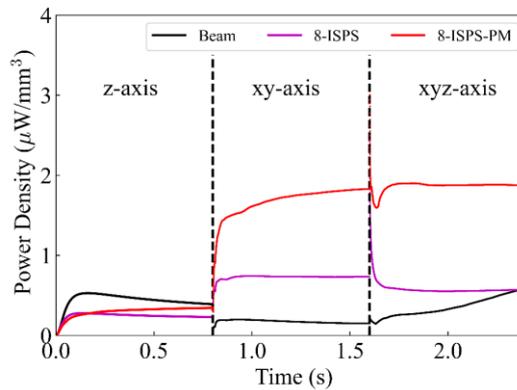


Figure 5 – Time-history response of rms PD for multi-direction random-frequency excitation with $u_0 = 14.48 \mu m$, $\Omega = 130$ Hz and $\sigma = 4$ Hz; comparative analysis of the cantilever-beam, 8-ISPS, and 8-ISPS-PM devices.

Transient simulations are carried out during 2.4s for all energy harvesting devices. A comparative analysis of RMS PD is presented in Fig. 5. Results show the influence of ambient vibration conditions in the performance of the 8-ISPS-PM device that employs inertial pendular masses to achieve multidirectional characteristics. Although the strategy of using pendular masses to convert energy from multidirectional excitations showed to be interesting, it needs to be analyzed with attention considering either the device or the ambient vibration characteristics in the design process. Another important aspect to be pointed out regarding the pizza-shaped harvesters is the geometry slicing which breaks the connection between some vibration modes.

In Figure 6, MSS energy harvester with coupled vibration modes are investigated under multidirectional excitations with uncertainties in the frequency spectrum. The USS device replaces the pendular masses of MSS design by equally weighted tip masses coupled to the substrate surface, presenting only unidirectional sensitive characteristics. Results show that for out-of-plane vibration (z -axis direction), the beam device presented worse performance when compared with both the USS and the MSS devices due to the broadband spectrum characteristic of the excitation. Under this condition, the USS device showed higher levels of PD compared with the proposed MSS device. This can be attributed to the tip masses being close to the substrate which causes higher oscillations of the structure and therefore, more energy is generated by the piezoelectric patches. For the in-plane vibration (xy -axis direction), the MSS device shows the best performance compared with the USS device providing higher levels of PD. Moreover, in the third region where a combination of in-plane and out-of-plane vibration is considered, the MSS device showed to be advantageous in terms of PD in comparison with the remaining device configurations. Under this condition, the beam device is more efficient than the USS device.

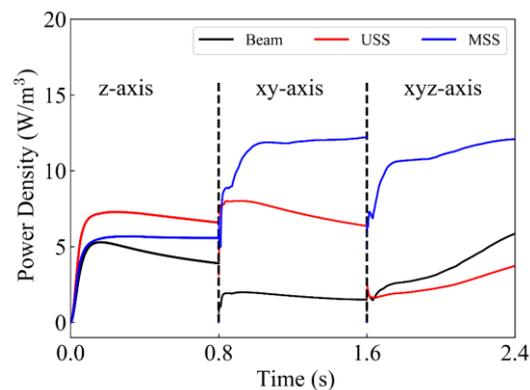


Figure 6 – Time-history response of rms PD for multi-direction random-frequency excitation with $u_0 = 14.48 \mu\text{m}$, $\Omega = 130 \text{ Hz}$ and $\sigma = 4 \text{ Hz}$; comparative analysis of the cantilever-beam, 8-ISPS, and 8-ISPS-PM devices.

In conclusion, the proposed finite-element-based optimization procedure showed to be an interesting approach for designing mechanical vibration-based multimodal piezoelectric energy harvesting devices to operate under multidirectional and broadband excitations. An important aspect to be pointed out is the influence of the ambient vibration conditions in the performance of the harvesters. Although the strategy of using pendular masses to extract energy from multidirectional excitations showed to be interesting, it needs to be analyzed with attention. The pendular mass devices can add additional damping to the system that attenuates vibration energy, reducing the energy harvesting capacity for long term extraction. Besides, pendulum mass can work as a vibration absorber, attenuating the structure vibration, which also reduce the energy harvesting capacity. These aspects are especially important for harnessing energy efficiently.

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