Extreme Mechanics Letters 22 (2018) 1–7

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

# A multi-modal energy harvesting device for low-frequency vibrations

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ARTICLE INFO

*Article history:*
Received 9 March 2018
Received in revised form 9 April 2018
Accepted 18 April 2018
Available online 24 April 2018

*Keywords:*
Energy harvesting
Nonlinear finite element
Very low frequency
Wind turbine

ABSTRACT

This paper presents an innovative design of a low-frequency multi-modal system vibration-based energy harvester (VEH) for powering wireless autonomous monitoring systems wind turbines of 30 kW. The main objective is to design an energy harvesting device capable to operate in a very low-frequency bandwidth (3 to 10 Hz) increasing as much as possible the operational bandwidth by enhancing the amplitude of the second mode of vibration. The electrical power performance is evaluated for four different energy harvesting designs, which are mainly composed of multi-beams cantilevers with tip masses. For the harvesting system with two multiple-beams trident, a rigid beam is selected to join them. This versatile geometric configuration offers the possibility to modify the vibration characteristics of the harvester in several alternative ways, not only by increasing the tip mass which may be not favorable from a structural viewpoint. The resonant frequencies values, the time voltage signals and the electric power are obtained through a finite element beam formulation early proposed by the authors, capable to modeling three dimensional systems. The numerical results are validated through experimental tests. Regarding the output power, the most promising design with two multiple-beams trident with a tip mass delivers 36.48 μW and 96.04 μW in the proposed range of operation (first two resonance frequencies 4.76 and 7.91 Hz, respectively) excited by 0.1 g of base acceleration. This clearly indicates that the device is a very good candidate for the proposed application of autonomous wireless monitoring, since the output power is larger than the minimum of 20 μW required.



## 1. Introduction

Sensing electronic devices is known for their small size and low power consumption. Commonly used sensors are ultrasonic sensors, weather, pressure, humidity and temperature transmitters. Mostly, the electrochemical batteries are the best choice today to power these sensors or electronic devices. Despite the advantages of batteries such as low cost, high energy density and small size, these have disadvantages such as environmental pollution, low durability and inconveniences to recharge, which implies great maintenance [1]. On the other hand, the evolution of alternative energy sources to power electronic devices with low power consumption is growing interest in the science community. In this sense, energy harvesters based on piezoelectric effect represent a very effective mechanism to convert mechanical into electrical energy [2]. Between them, mechanical vibrations as energy source for low-frequency energy harvesting is getting interest in the nowadays research topics [3,4]. In comparison with other mechanical sources, the excitation by low-frequency vibrations is really a challenge since the output power density of the energy harvester is low. From the work of [5], the attainable maximum power in an inertial (or base accelerated) device is governed by a cubic dependence on frequency and a linear dependence on mass, maximum displacement and amplitude of the excitation. In the last years, the researchers have focused on the concept of tuning the harvesters in the fundamental resonance frequency or broaden the bandwidth with the goal to increase the output electrical power employing different harvesting approaches. These energy harvesting devices are based on basically three methods to extract power: a hybrid piezoelectric–electromagnetic approach, a mechanical frequency up-conversion and single mechanical vibrations. The hybrid piezoelectric–electromagnetic method is one of the most commonly used approaches to harvest energy, which conceptually consists in using the attracting force between two magnets to tune the resonant frequency [6–10]. However, this energy conversion mechanism is commonly known by the low output power, which represents a disadvantage to energize small electronic devices. For example, a recent work [7] reported a maximum electrical power of 82.5 μW of a harvester with a spherical permanent

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https://doi.org/10.1016/j.eml.2018.04.003
2352-4316/

magnet, excited by 3 g and in a frequency bandwidth from 10 to 19 Hz. This electrical power can be improved reaching to 245.6 μW across a 1.2 kΩ load for a device with a magnetic shape memory allow attached to a macro fiber composite cantilever. The second approach, which consists in converting low-frequency vibration into high frequency vibration, known as mechanical frequency up-conversion, is recently applied [11–13]. For example, experimental results of a piezoelectric energy harvester using flexible side-walls have been recently presented in the literature [13]. They reported an output power of 175 μW when the harvester is excited by 2 g, having an operational frequency bandwidth of 5 Hz (from 2.5 to 6 Hz approximately). Finally, the third and the most popular investigated approach is when the energy source is from mechanical vibrations under base acceleration excitation [5,14–17]. Many researchers are working in harvester devices tuning the first resonance mode at high values of frequency due to the high density power offered by these systems at high frequencies [18]. However, these types of VEH with high resonant frequencies are not useful when the structure is excited at low-frequencies. Recently, a researcher group evaluated a wideband piezoelectric energy harvester comprising an M-shaped cantilever, which can be tuned to the first three bending modes of vibration in a frequency range from 13 to 25 Hz excited by 1 g of acceleration [19]. The numerical analysis of the harvester is performed using COMSOL Multiphysics and the results are validated by means of experimental tests. They concluded that the design is effective in terms of broadening the operational bandwidth with three considerably high values of voltage (17, 27 and 10 V approximately). More recently, other authors studied the performance of four different designs of energy harvester [20]. They presented the best performance among four designs, which has three resonance peaks with an operational frequency bandwidth from 18 to 26 Hz, obtaining a maximum electrical power of 1.9, 0.72 and 0.45 μW (wrongly informed by the authors in mW [20]) for the three resonance peaks, respectively. In this last case there is no information about the acceleration of the excitation. Additionally, their proposed designs have some disadvantages: a low output power, a decrement of the electrical power as the resonance frequencies increase, and a large operational range (from 5–35 Hz). In order to solve these drawbacks, the purpose in this work is to design, analyze and test a multi-beam piezoelectric energy harvester focusing on maximizing its power output for very low frequencies (3 to 10 Hz). Our proposal consists in enhancing the operational bandwidth by increasing the amplitude of the second mode of vibration and diminishing the frequency value of the resonant peaks. To this end, four energy harvesting devices are presented and analyzed. In the first part of the study its dynamic behavior is evaluated. With the idea to maximize energy from a very low frequency vibration we focus on designing a VEH to have similar amplitudes in the first and second resonance peaks for a given frequency bandwidth. This necessarily broadens the operational frequency of the harvester to provide energy to wireless transmission systems or temperature sensors in low frequency environments such as wind turbines of 30 kW, which have an operational frequency bandwidth ranging from 0.5 to 10 Hz. The electrical power that requires these electronic devices to operate is at least 20 μW [21]. The present article is organized as follows. After the introduction, the design and modeling of the rotating harvester are presented in Section 2. Section 3 contains the experimental setup. Section 4 shows the results of the voltage time response, the voltage and power generation compared with the experimental results. Finally, Section 5 presents the conclusions.

## 2. Design and modeling

Fig. 1 shows the four proposed designs of our energy harvesting system. The first design consists in multiple beams called by the authors multiple-beams trident (MBT). It is built by multiple aluminum beams with a mass at the free end made of steel. This first prototype is similar to those presented previously, [19,20] but differs in its dynamic behavior due to the boundary condition. In their model the central beam is fixed and the structure is based on the cantilever beam concept with two tip masses on the secondary beams. In our case, the lateral beams are fixed to a frame and clamped to a vibrating base (see Fig. 1a), and the central beam has a mass at the free end. On the other hand, the models presented before [19,20] operate for a frequency range superior than the one proposed in this work. Generally speaking, it is easy to demonstrate that the resonance frequencies can be reduced by the incorporation of a tip mass. However, the influence of a tip mass in multiple-beams design is not simple to predict. This effect is properly analyzed with the second design (MBTM) where the tip mass is increased approximately three times (see Fig. 1b). This allows us to study the advantage of incorporating a secondary multiple-beams trident in comparison with incorporating an extra tip mass. However, the addition of mass cannot continue without a limit. The mass is selected in order to avoid large displacements of the structure (the tip displacement must not exceed approximately 10% of the total length of the structure) with the intention of not having structural damage in a resonant condition. In the third harvester design (MBT2), a second multiple-beams trident is added as shown in Fig. 1c. With this innovative design we want to improve the operational bandwidth of the harvester, trying to obtain similar amplitudes in the first and second bending mode. Finally, two extra masses are placed at the free ends of the second trident in order to analyze its influence both in the frequencies and in the second amplitude mode, thus obtaining the final design of the harvesting system MBT2M. In order to operate at a low frequency range, the tip masses and dimensions of the multi-beams are assessed to tune their natural frequencies between the range of 3 and 10 Hz. After evaluating the dynamic behavior of the systems, we study the influence of the electrical load over the generated voltage and power density.

### 2.1. Electromechanical model

With the aim to analyze the dynamic behavior and generated power of the energy harvesters, a piezoelectric beam formulation developed previously by the authors [22] is implemented by means of a geometrically nonlinear finite element with six mechanical degrees of freedom and one electrical degree of freedom per node. Using Timoshenko beam theory for the mechanical domain and a first-order theory for the electrical field, the electromechanical equations of motion are derived using d'Alembert principle. A brief description of the finite element formulation is presented here. Detailed discussion of this finite element formulation can be found in the cited Ref. [22]. The electromechanical equations of motion, formulated in matrix form, can be expressed as:

$$\boldsymbol{K_T}\hat{\boldsymbol{U}} + \boldsymbol{D}\hat{\boldsymbol{V}}_{\boldsymbol{G}} + \boldsymbol{M}\hat{\boldsymbol{a}}_{\boldsymbol{G}} - \boldsymbol{\Theta}\hat{\boldsymbol{V}} = \boldsymbol{F_E} \tag{1}$$

$$\boldsymbol{\Theta}^{\boldsymbol{T}}\hat{\boldsymbol{U}} + \boldsymbol{C_P}\hat{\boldsymbol{V}} + \boldsymbol{Q_E} = \boldsymbol{0} \tag{2}$$

where the damping matrix is:

$$\boldsymbol{D} = \alpha\boldsymbol{M} + \beta\boldsymbol{K_T} \tag{3}$$

and their coefficients are modeled through proportional models with frequency varying coefficients [23], which depend on the velocity and theirs values are experimentally determined. $\hat{\boldsymbol{V}}$ and $\hat{\boldsymbol{U}}$ are the nodal voltage and displacement vectors. $\hat{\boldsymbol{V}}_{\boldsymbol{G}}$ and $\hat{\boldsymbol{a}}_{\boldsymbol{G}}$ are the nodal velocity and acceleration vectors. $\boldsymbol{F_E}$ and $\boldsymbol{Q_E}$ are the mechanical and electrical loads. $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{K_T}$ is the total stiffness matrix which includes the material and the geometric

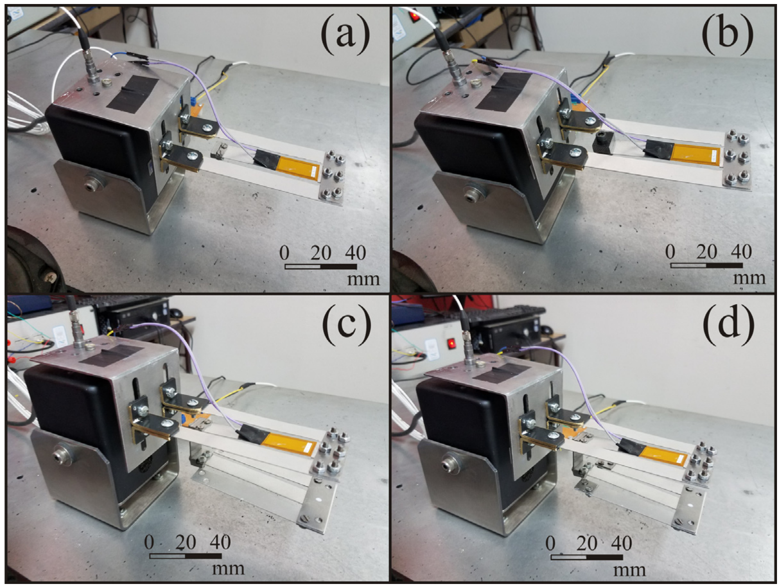


**Fig. 1.** The four proposed designs of the multimodal vibration piezoelectric energy harvesters. (a) MBT, (b) MBTM, (c) MBT2 and (d) MBT2M.

**Table 1**
Material properties for aluminum, steel, and MFC 2814 P2.

| Aluminum | Value | MFC 2814 P2 | Value | Steel | Value |
|---|---|---|---|---|---|
| $E$ | 67 GPa | $E1$ | 30.3 GPa | $E$ | 210 GPa |
| Density | 2700 kg/m$^3$ | $E2$ | 15.85 GPa | Density | 7850 kg/m$^3$ |
| | | Density | 5440 kg/m$^3$ | | |
| | | Piezoelectric constant $d_{31}$ | −2.1 E+2 pm/V | | |
| | | Capacitance | 30.78 nF | | |

stiffness. $\boldsymbol{\Theta}$ and $\boldsymbol{C_P}$ are the electromechanical and the capacitance matrices, respectively [22].

The advantage of the developed formulation is the possibility of modeling three-dimensional electromechanical energy harvesting devices using a one-dimensional formulation, which permits to make fast and simple simulations of complex tridimensional energy harvesting systems. In this sense, the voltage signal and electric power generation can be calculated varying the electric load, which simulates the power consumption of a small electronic device. Additionally, we validate the formulation by means of experimental tests showing the reliability of proposed methodology.

The results obtained are validated through a comparison with experimental data. It is important to highlight the usefulness of the finite element formulation, because it is not possible to obtain (approximate) analytical solutions in this case as in most existing devices based on the cantilever beam concept [15,16,24]. However, there is a tendency in the last years to design energy harvesters with more complex geometries [19] and the use of finite element software packages such as Abaqus or ANSYS [25–27] is quite widespread despite of the large computational costs even for simple geometrical configurations. Other approaches prefer to perform experimental tests without an exhaustive numerical analysis of the obtained voltage, which is also a drawback [7,11,20,28–30].

## 3. Experimental setup

Fig. 2 shows the experimental setup to evaluate the dynamic behavior of the piezoelectric energy harvesters. The prototypes are excited using an electrodynamic shaker manufactured by Labworks ET-132. The input signal is generated by an arbitrary Rigol DG4062 wave generator. The signal is amplified using a home-built amplifier. The acceleration signals are acquired using a PCB accelerometer with a sensitivity of 98.7 mV/g and the voltage signals are acquired via a National Instruments NI9234 data acquisition module and post-processed by a Matlab code. The attenuator is a home-built circuit that scales the voltage signal due to the limitation of the data acquisition system and regulates the electrical resistance. All the proposed harvesting systems are excited by a sinusoidal wave form acceleration of amplitude 0.02 g (1 g = 9.8 m/s$^2$) at different frequencies varying the electric load from 10 to 1000 kΩ. Table 1 shows the material properties of the aluminum, steel and piezoelectric layer MFC 2814 P2 used to build the prototypes. It is important to mention that a linear interpolation through the thickness for the electric potential is used because the electric field of the piezoelectric material MFC 2814 P2 is constant in the thickness [31].

## 4. Results and discussions

With the goal of showing the advantages of the proposed prototypes, we obtain the dynamic behavior and voltage generation of the dynamical systems. Fig. 3 shows the normalized mode shapes corresponding to each resonance frequency and the typical voltage generation at different frequencies and $a = 0.02$ g (1 g = 9.8 m/s$^2$) of base acceleration for all the proposed cases. In order to simulate the power consumption of a small electronic device, an electrical load with a resistance of 1 MΩ is used. The damping ratio of the harvester is evaluated by means of the experimental tests, considering the first two frequencies corresponding to the bending modes [23]. Qualitatively and quantitatively comparisons of the results obtained from numerical simulations and the experimental tests also are showed in Fig. 3. There, it is possible to observe a remarkable correlation between the magnitude and frequencies of the resonance peaks.

In Fig. 3a, the first and second bending resonant frequencies for the first model give 10.80 Hz and 14.42 Hz, having a maximum

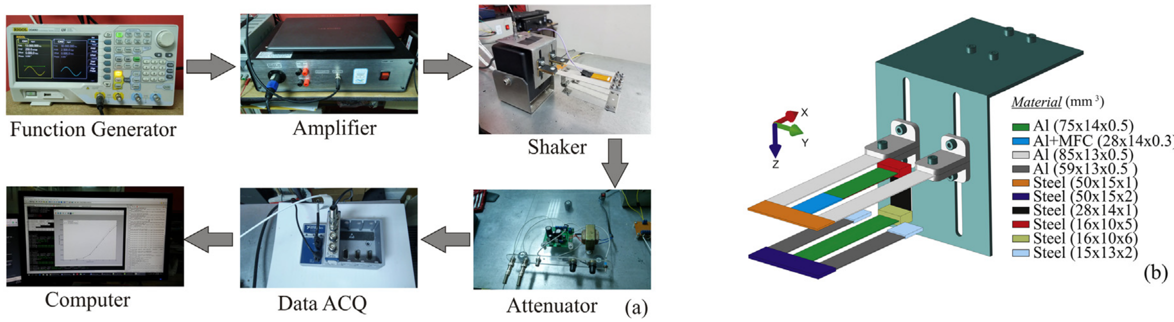


**Fig. 2.** (a) Experimental setup to test the piezoelectric energy harvesters and (b) Geometric dimensions and materials of MBT2M design.

displacement in the tip mass of 0.4 mm and 3.1 mm, respectively. This configuration of multiple beams with a tip mass of 6.4 gr gives a frequency bandwidth of 4 Hz with two resonance peaks of different amplitude. In the second proposed design (MBTM) the tip mass is increased from 6.4 to 18 gr. In this case, the first and second resonance frequencies decrease to 7.81 Hz and 11.72 Hz, having maximum displacements of 3.2 mm and 1.6 mm for each resonance peak (see Fig. 3b). Concerning to the third harvester prototype (MBT2) illustrated in Fig. 1c, a second multi-beam trident is attached below the first trident by means of a rigid beam. In this case, the whole added system (the second trident and the rigid beam) has a mass of 44.4 gr, which is approximately 2.5 times larger than the tip mass of the second harvesting system (MBTM). This geometrical distribution offers an alternative design with a similar dynamic behavior compared to MBTM, for low resonance frequencies and without exceeding the displacement limit imposed by the linear assumption. In this case, the modal analysis gives 4.91 Hz and 8.33 Hz with a maximum displacement of 0.7 mm and 1.5 mm, for the first and second mode, respectively (see Fig. 3c). In the last proposed harvesting system (MBT2M) two extra masses of 3.3 gr are placed at the free ends of the second trident, as illustrated in the Fig. 1d. The first and second bending frequencies have been reduced to 4.76 Hz and 7.91 Hz, with a maximum displacement of 1.2 mm and 2.4 mm, respectively (see Fig. 3d). The natural frequency values, the damping parameters and the maximum displacements corresponding to each energy harvester are listed in Table 2.

Analyzing these results, it is possible to point out the following remarks. The addition of an extra mass in the second multi-beam trident (MBT2M) reduces each natural frequency approximately 50% in comparison with the first proposed system (MBT). As it is expected in the MBT2M model, the amplitude of the displacement increases three times compared with the MBT design for the first mode, and increases approximately 1.3 times with respect to the second mode. This represents an advantage for this model because it is possible to reduce the natural frequency of the system and to increase the displacements, which implies an increment in the output voltage and the electric power, as will be appreciated in the following figures.

Concerning voltage generations of the different prototypes, Fig. 3a shows the peak voltages for the first model (MBT). A good agreement between both numerical and experimental results is observed. For the resonance frequency at 10.80 Hz, an output voltage of 0.33 V is obtained, whereas the harvesting system generates 2.29 V for the second resonant frequency at 14.42 Hz. With the addition of mass, the second harvester MBTM increases the generated voltage in the first resonance peak to 1.50 V at 7.91 Hz, but decreases the voltage generation in the second peak to 0.96 V at 11.72 Hz (see Fig. 3b). Although the voltage increases more than four times, it can be observed a deep well between both resonances peaks reducing the operational bandwidth of the harvester.

The voltage performance of the MBT2 prototype is presented in Fig. 3c. In comparison with the MBTM harvester, the voltage decreases to half its value, reaching 0.72 V in the first mode. However, in the second mode the generated voltage is increased from 0.96 to 1.78 V. Although this last model MBT2 meets the requirement design previously set, the operational bandwidth could be improved increasing the voltage generation in both modes. To this end, the addition of extra masses to the second trident for the MBT2M harvester, almost doubles the output voltage compared to its previous value, giving a voltage of 1.34 V at the first resonance peak and 2.70 V (see Fig. 3d) for the second peak. The next analysis consists in the comparison of the electrical power performance for all the proposed systems. Fig. 4 shows the output power as a function of electrical load from 10 to 1000 kΩ for the first and second resonant frequencies. To evaluate harvesters performances, the generated power is computed according to $P = V^2/R$, where $V$ is obtained by solving Eqs. (1) and (2). The maximum power obtained is 2.69 μW across the electrical load of 500 kΩ at the first resonance frequency and it corresponds to the second harvester model MBTM excited at 0.02 g of base acceleration (see Fig. 4a). In the case of the second bending mode (Fig. 4b), the MBT harvester gives the maximum output power of 7.68 μW at 500 kΩ. However, according to requirement previously set (very low frequencies and improve the voltage generation in both modes), the last model (MBT2M) is a good candidate for the proposed application, delivering a maximum output power of 1.37 and 7.37 μW for extremely low natural frequencies (4.76–7.91 Hz) at 0.02 g of base acceleration across load resistance of 500 kΩ.

In order to compare our designs with some existing multimodal piezoelectric harvesters available in the literature, firstly it is important to mention that an objective comparison between different harvesters is difficult, since the maximum power is ruled by a cubic dependence on frequency and a linear dependence on mass, displacement and amplitude of excitation. However, making an effort to do a fair comparison, Table 3 shows comparative results between our proposal and two devices with similar structural features developed by different authors [19,20]. The operational frequency bandwidth, electric resistance, acceleration level, generated voltage and electric power are presented for the devices of [19,20] and our energy harvester. For the device cited in Ref. [19], which uses three PVDF-type piezoelectric sheets instead of one (our device), the generated voltage for open circuit is 16 and 25 V for the first two modes in a frequency range between 13 and 25 Hz and 1 g of base acceleration. For the device cited in [20], which uses one MIDE QP16N, the generated voltage is 0.88 and 0.46 V for the first two modes using an electric load of 1 MΩ. This last case represents an output power of 0.77 and 0.21 μW for the first and second modes, respectively. Additionally, it is important to mention that in [20] there is no information about the applied excitation. Regarding our energy harvester, instead, the generated voltage at 0.1 g of base acceleration results 6.04 and 9.80 V for

**Table 2**
Natural frequencies and damping parameters of the proposed energy harvesting systems.

| Harvesting system | *fn* [Hz] | | Damping ratio | | Max. displacement [mm] | |
|---|---|---|---|---|---|---|
| | Mode #1 | Mode #2 | $\zeta_{\#1}$ | $\zeta_{\#2}$ | Mode #1 | Mode #2 |
| MBT | 10.80 | 14.42 | 0.013 | 0.006 | 0.4 | 3.1 |
| MBTM | 7.81 | 11.72 | 0.016 | 0.007 | 3.2 | 1.6 |
| MBT2 | 4.91 | 8.33 | 0.010 | 0.005 | 0.7 | 1.5 |
| MBT2M | 4.76 | 7.91 | 0.010 | 0.006 | 1.2 | 2.4 |

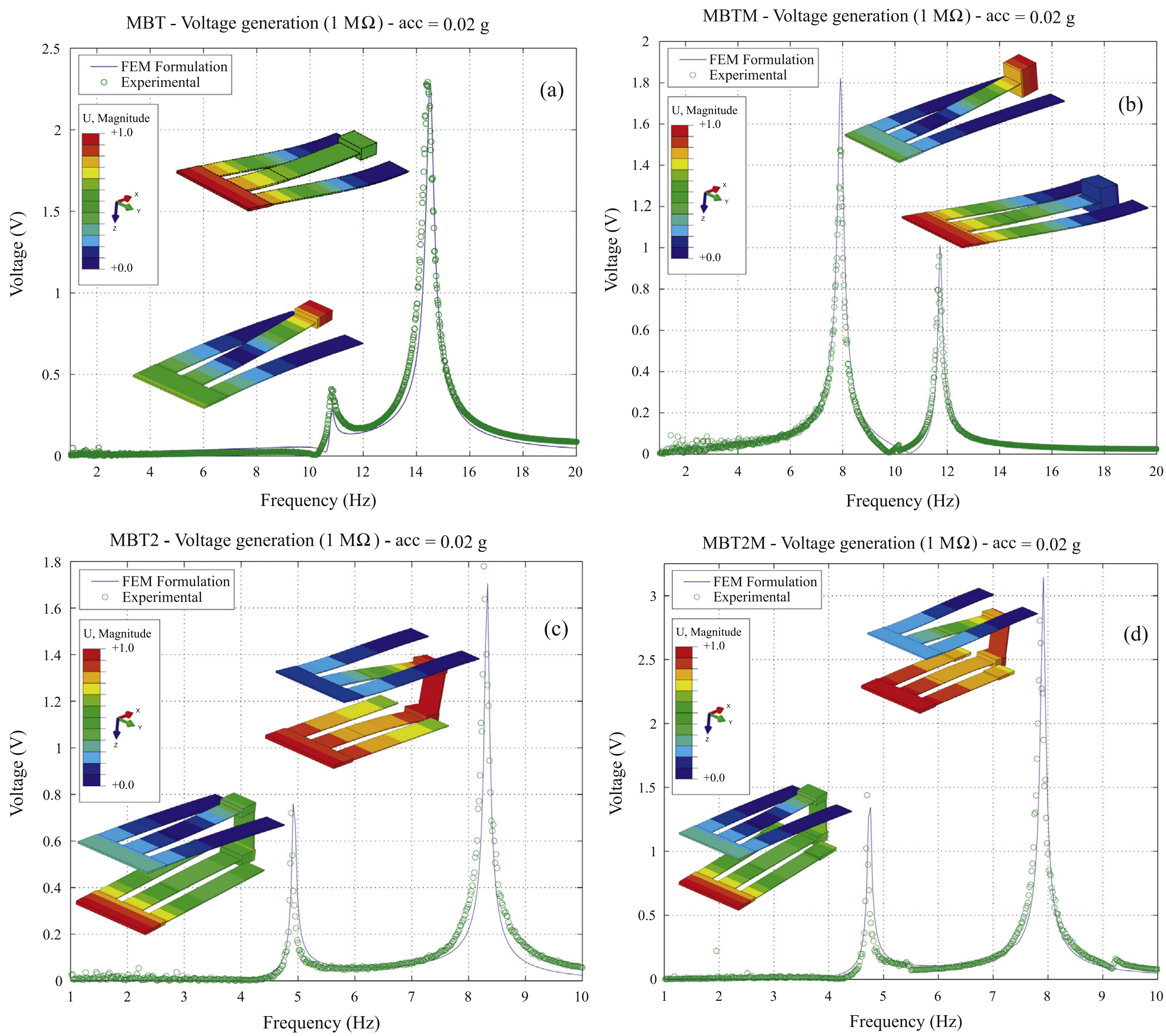


**Fig. 3.** Voltage generation for 1 MΩ at $a = 0.02$ g base acceleration for the four harvester designs: (a) MBT, (b) MBTM, (c) MBT2 and (d) MBT2M.

**Table 3**
Comparison between the last proposed harvester (MBT2M) and the harvesters [19] and [20].

| Harvesting system | *R* [MΩ] | Frequency [Hz] | | Acceleration [*g*] | | Voltage [V] | | Power [μW] | |
|---|---|---|---|---|---|---|---|---|---|
| | | *f* #1 | *f* #2 | | | *f* #1 | *f* #2 | *f* #1 | *f* #2 |
| Sun et. al. [20] | 1 | 18.18 | 23.60 | – | | 0.88 | 0.46 | 0.77 | 0.21 |
| | 0.1 | | | – | | 0.45 | 0.30 | 2 | 0.90 |
| Wu et. al. [19] | OC (>10) | 14.30 | 17.80 | 1 | | 16 | 25 | – | – |
| MBT2M | 1 | 4.76 | 7.91 | 0.1 | Sim | 6.33 | 11.62 | 40.06 | 135.02 |
| | | | | | Exp | 6.04 | 9.80 | 36.48 | 96.04 |
| | 0.1 | 4.76 | 7.91 | 0.1 | Sim | 2.16 | 5.65 | 46.65 | 319.23 |
| | | | | | Exp | 2.20 | 5.20 | 48.40 | 270.40 |

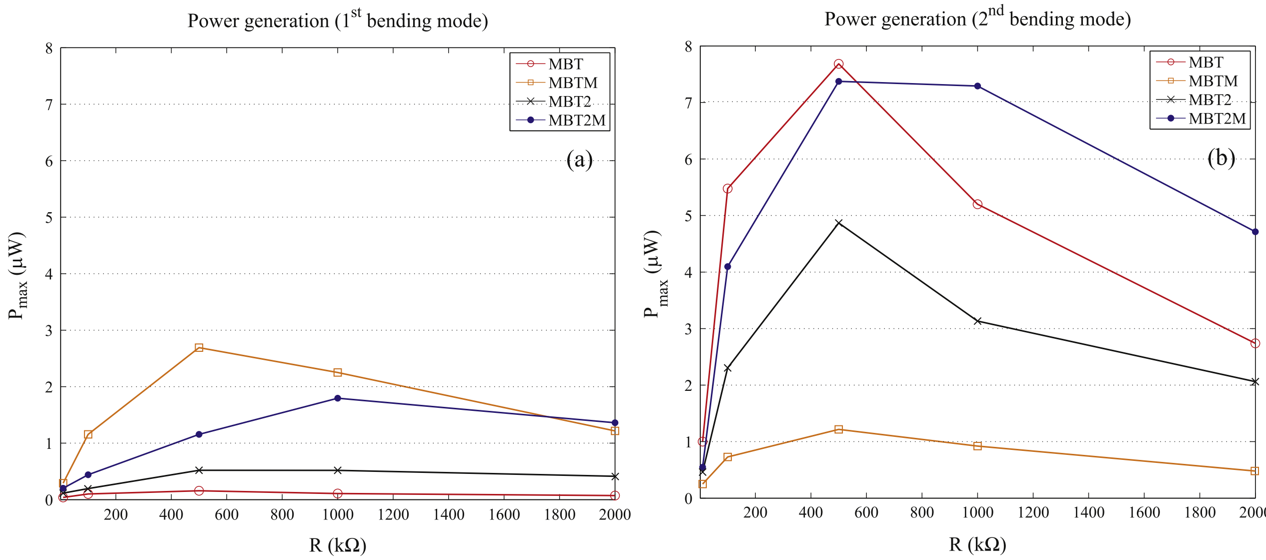


**Fig. 4.** Power output response as a function of electrical load for MBT, MBTM, MBT2 and MBT2M at 0.02 g: (a) first bending mode, (b) second bending mode.

the first and second modes, respectively, in a frequency range that it is approximately 4 times lower than [19] and 3 times lower than [20]. In relation with the output voltage, our device delivers approximately half the output voltage while it is excited by an acceleration 10 times lowers than [19]. Regarding the output power, our device generates 36.48 and 96.04 μW for the first and second mode, respectively, using an electric load of 1 MΩ, which is larger than the minimum of 20 μW to power a wireless transmission system [21] or a temperature sensor (LM35, for example). In this sense, the power requirement is always lower than the generated power at both frequencies.

## 5. Conclusions

In conclusion, this paper presents several alternatives in the design of multimodal piezoelectric harvesters to provide energy to wireless autonomous monitoring systems of wind turbines of 30 kW for very low frequencies (3–10 Hz). The most common multimodal devices consists of multiple beams oriented in one plane, [19,20] where the structural design is restricted to the addition of mass to improve its operational frequency bandwidth. However, our alternative for a multimodal energy harvesting system not only reaches a significant voltage generation at very low frequencies but also prevents the system from having large excursions of the mass (in the limit imposed by linearity) by means of an innovative mechanical design. A very good agreement between the numerical predictions and the experimental tests are obtained in the four prototypes analyzed. From the results, it is possible to conclude that the MBT2M harvester presents the best configuration according to the requirement of having a large operational bandwidth and high output power.

Summarizing, our proposed vibration-based energy harvester (VEH) has the following main contributions:

- The proposal of a multi-modal prototype with extremely low natural frequencies (4.76–7.91 Hz).
- The possibility to modify the vibration characteristics of the multi-modal harvester not only by increasing the tip mass.
- The increment of the generated voltage in the second mode of vibration and the shift of the operational frequency bandwidth to very low frequencies. The generated power reaches 36.48 and 96.04 μW for the first and second mode using an electrical load of 1 MΩ, respectively, which is larger than the minimum to power a wireless transmission system or a temperature sensor.

In future works, the following items will be considered:

- A multi-beam cantilever's based improved design for energy harvesting at very low frequency in rotational motion.
- A geometrically non-linear finite beam-type element capable for modeling three dimensional energy harvesters in rotational motion.
- A wireless data acquisition system based on Arduino technology to avoid slip-ring mechanisms.

## Acknowledgments

The authors would like to thank the supports financial from CONICET (PIP No: 11220120100346), Universidad Nacional del Sur, Universidad Tecnológica Nacional and ANPCyT under grant PICT 2013-2065.

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