On the Performance Improvement of Piezoelectric Energy Harvesters

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***Abstract*—Among the available solutions to harvest energy from vibrating and nonvibrating sources, piezoelectric bimorphs seem to be a suitable choice because of their capability to directly convert applied strain energy into usable electric power. In this work, we review the techniques adopted to increase the specific power per unit of volume of piezoelectric scavengers. The design goal is to obtain a uniform stress distribution on the piezoelectric layers, in order to exploit the electromechanical energy conversion capability of the whole material. Two approaches are then followed to improve the performance: by designing an optimal shape of the device or by imposing an optimal bending deflection. For both strategies, results from numerical models and experimental tests are compared.**

***Index Terms*—Energy harvesting, piezoelectric material, bending deflection, electro-mechanical coupling**

I. Introduction

The technology of energy harvesting has received a great deal of attention in recent years, as a means of converting and exploiting ambient energy for supplying portable and wireless electronic devices with an extended lifespan. Converting the energy available in the same environment in which devices are located can be a valid method to fulfill the requirements of autonomy and miniaturization. Among different materials and transduction mechanisms, piezoelectric harvesting systems have received the greatest deal of attention because of their capability to directly convert applied strain energy into usable electric power and the ease with which they can be integrated into an electronic system [1-4]. In particular, piezoelectric bimorphs, with two layers of piezoelectric material bonded onto a supporting metallic shim, are useful for this purpose. Indeed, bimorphs can be subjected to relatively high mechanical strains even under moderate bending loads. Figure 1 shows a conventional piezoelectric bimorph with a rectangular shape. This type of device is usually adopted for generating electrical energy from vibrations: one end of the beam is clamped to the vibrating source, while the other end is free. An inertial mass is often added at the free end in order to maximize the tip displacement and also to tune the system's resonant frequency to that of the excitation [5]. Vibrations produce a mechanical strain, which is converted, via electromechanical coupling, into an electric charge distribution that induces an electric field between the upper and the lower electrodes. Electric power can also be obtained under nonvibrating loading, as discussed, for example, in [6]. One goal is to design an optimal harvester configuration that maximizes the mechanical strain and, in turn, the electrical power extracted from a given ambient source. Conventional cantilevers with a rectangular shape, when subjected to bending, are characterized by a nonuniform average strain level in the piezoelectric layer. In order to increase the average mechanical strain and thus the piezoelectric conversion efficiency, various alternative solutions characterized by nonconventional geometries have been proposed in the literature [7-11]. Other strategies, aimed at optimizing the deformed shape of the device rather than its geometry, have also been investigated [12]. After a brief account on the concept of uniform bending strain in beams, in this work, we present two strategies to improve the performance of vibrating and nonvibrating piezoelectric bimorphs.

Figure 1. Conventional rectangular piezoelectric scavenger.

II. Uniform Bending Strain In Beams

In order to introduce the basic concepts and equations, the behavior of a homogeneous and isotropic cantilever under bending, as represented in Fig. 2(a), is investigated

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here. The cantilever is clamped at one side and loaded by a tip force, F, at the opposite end.

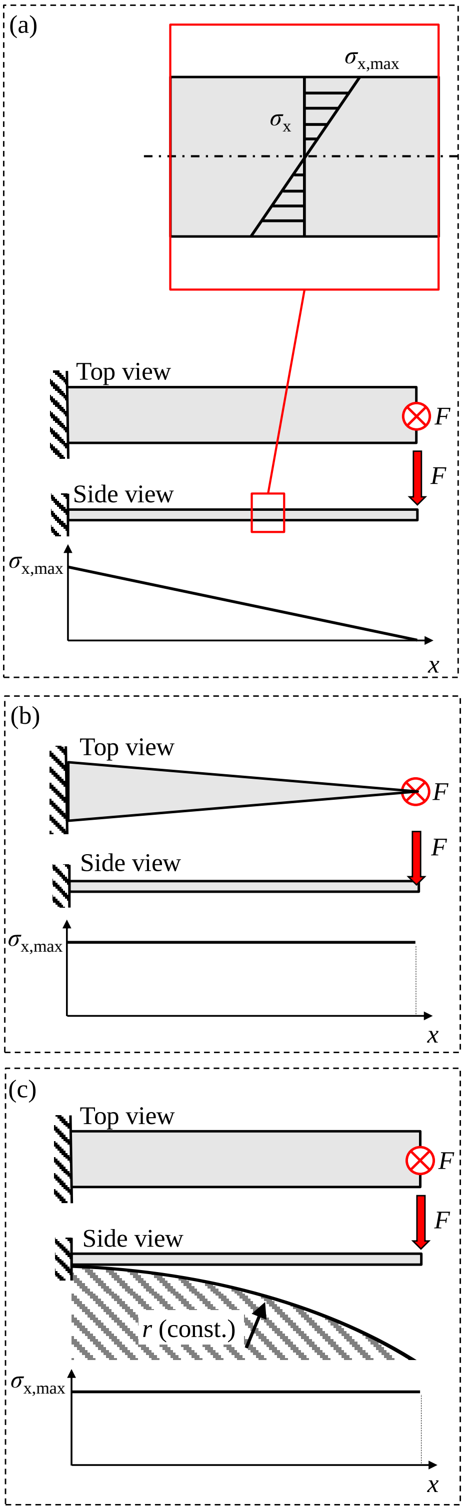

Figure 2. Cantilever under bending: (a) rectangular, (b) triangular, and (c) rectangular forced to have a circular curvature.

This configuration is used to gain insights into the physics of the problem and to guide the understanding of the design solutions for piezoelectric harvesters presented later on. In fact, in these devices, the electrical output power is directly connected to the distribution of mechanical stress (or strain) on the piezoelectric element.

For the beam in Fig. 2(a), the tip force, F, produces a bending moment, M_z, and, in each cross section, a linearly distributed bending stress, which attains its maximum value at the outermost surface:

$$\sigma_{x,\max} = \frac{M_z}{W_z}, \tag{1}$$

where W_z is the elastic section modulus. For a rectangular cantilever, the section modulus can be evaluated as

$$W_z = \frac{bh^2}{6}, \tag{2}$$

and the bending moment at position x is

$$M_z = F(l - x), \tag{3}$$

where l, b, and h are the beam's length, width, and thickness, respectively. Obviously, the higher the tip force F, the higher the maximum stress $\sigma_{x,\max}$. The force F, however, can be increased until the maximum stress reaches the material strength limit. It is evident, by substituting Eqs. (2) and (3) into Eq. (1), that the maximum stress decreases from the fixed end to the free end. Therefore, only a limited portion of material close to the fixed end is actually loaded at the maximum stress. In analogy with the theory of flexural springs, the coefficient quantifying the amount of "active" material in the configuration of Fig. 2(a) is equal to 1/9 [13]. Therefore, a way to increase this coefficient is to obtain a more uniform stress distribution along the cantilever. This goal can be achieved in two ways: by designing a customized shape (hence, W_z in Eq. (2) will be modified) or by loading a rectangular-shaped cantilever with a constant bending moment (hence, a different expression of M_z in Eq. (3) will be obtained). As an example, a beam with a triangular shape allows obtaining a uniform stress distribution along the cantilever surface [see Fig. 2(b)]. Considering b as the beam width at the clamp, Eq. (2) becomes

$$W_z = \frac{b(l - x)h^2}{6l}. \tag{4}$$

A stress independent of the coordinate x (i.e., a uniform stress) results by substituting Eqs. (3) and (4) into Eq. (1). With this strategy, the aforementioned coefficient that accounts for actively loaded material then increases up to 1/3 [13]. Another strategy is related to the optimal deformation. If a constant bending moment M_z is applied on a rectangular beam, it can be demonstrated [12] that the beam deforms according to an arc with a constant curvature $1/r$.

$$\frac{1}{r} = \frac{M_z}{EI_z}, \tag{5}$$

where E is the elastic modulus and I_z is the second moment of area. Therefore, the arc-shaped deformation under the constant bending moment can be exactly replicated by forcing the beam to follow the shape of a cylindrical support, as depicted in Fig. 2(c). In the following, the two approaches to increase the mechanical strain will be applied to piezoelectric bimorph beams.

III. Optimal Shape Design

Electromechanical coupling depends on the electric capacitance, which in turn depends on both the area and the shape of the piezoelectric device. In order to maximize energy conversion, in the literature, it is thus suggested to cover the largest possible area of the device with piezoelectric material [1]. However, if the surface is covered by piezoelectric material regardless of the strain state, the overall performance can be limited, since the highest conversion can be achieved only if every portion of the piezoelectric material is strained close to its strength limit. Moreover, an averaging effect is also obtained, since the electric charge resulting from mechanical strain is uniformly distributed over the piezoelectric layer. As already pointed out, the design goal is that of shaping the surface of the piezoelectric layer such that, for a chosen vibration mode, the piezoelectric material undergoes the maximum mechanical strain. Considering vibrating devices, each mode would imply a different optimized scavenger shape. However, if the main aim is to make use of the first bending resonance of the cantilever, the static approach discussed in Section II seems valid, as it allows the whole material to be loaded at the maximum stress and strain. The geometry of the structure can therefore be designed to obtain the maximum stress state, constant along the beam. In the conventional rectangular scavenger, the bending moment and the resulting stress decrease linearly from the clamped end to the free end. On the other hand, according to Fig. 2(b), a triangular beam shape allows obtaining a uniform stress distribution along the cantilever surface. Since the scavenger is usually equipped with a tip mass at the free end, this optimized shape can be approximated by a trapezoidal one, referred to as trapezoidal shape in the following. In Fig. 3, the distribution of maximum stress $\sigma_{x,max}$ is calculated for different b_1/b_2 ratios, ranging from rectangular ($b_2 = b_1$) through trapezoidal up to triangular ($b_2 = 0$) configuration. All shape geometries share the same width at the base. The stress distributions are compared in terms of the dimensionless stress. It is clearly evident that the trapezoidal shape provides a more uniform stress (or strain) distribution compared to the rectangular one, thus providing the possibility of extracting higher relative power from the piezoelectric layer.

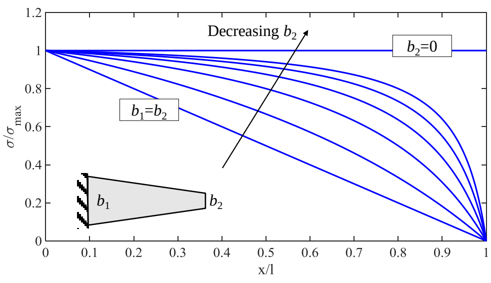

Figure 3. Stress distributions along the scavenger length computed for different “trapezoidal” shapes.

A. Numerical Simulations

Several analytical models are available in the literature to describe the electromechanical behavior of piezoelectric cantilevers with different shapes under sinusoidal base excitation, as proposed in [14]. Despite being helpful in defining the relevant parameters for the harvested power levels, these models are somewhat simplified. In order to obtain a more detailed description of the electromechanical behavior of the system, involving effects such as charge distribution, numerical models are adopted [12].

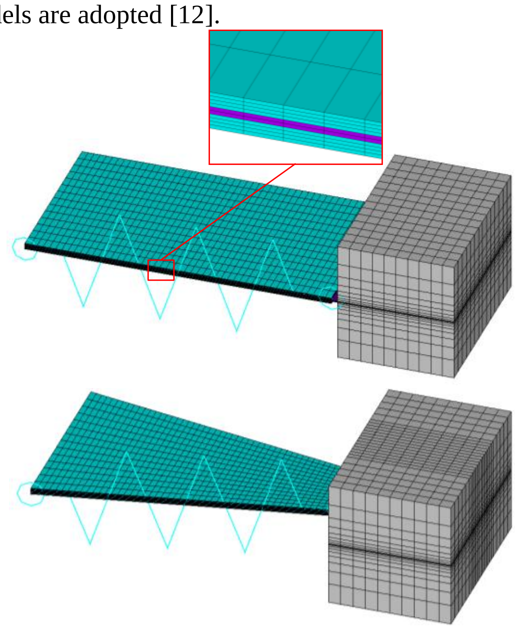

Figure 4. Coupled-field FEM of the rectangular and the trapezoidal scavengers.

In Fig. 4, an example of a coupled-field electromechanical finite element model (FEM) (rectangular and trapezoidal geometry) is shown. Solid elements are adopted for the metallic layer and the inertial mass, whereas piezoelectric layers are modeled with solid elements with four degrees of freedom at each node (three components of mechanical displacement and the electric potential). In order to investigate the harvested power, the piezoelectric layers are connected via an electric circuit element, representing a resistor. The condition of having a pure resistive load is not necessarily the most realistic one, since a capacitor can be connected to the piezoelectric bimorph to store electrical energy. A resistive load, however, is simple and useful for an immediate comparison of the harvested power levels. To calculate the power generated on the studied geometries, a forced dynamic (harmonic) analysis is implemented. Constant-amplitude sinusoidal acceleration is applied at the cantilever’s fixed base. A sensitivity analysis is performed by calculating the voltage distribution and the produced power in relation to the applied resistive load R_L. A comparison of the relative power obtained from the rectangular and the trapezoidal configuration, as a function of R_L, is shown in Fig. 5, where the increase in performance is clearly evident.

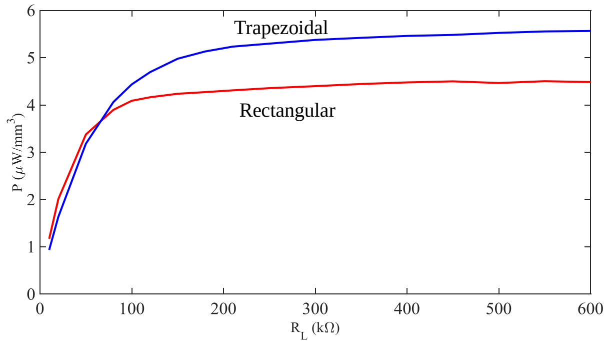

Figure 5. Numerical results in terms of specific power.

B. Experimental Measurements

The usual experimental setup used for model validation includes a shaker to impose oscillating displacement on the clamped end of the piezoelectric beam, a signal conditioner to control the input signal, a low-mass accelerometer to have feedback on base displacement, and a laser vibrometer to measure the displacement values of the scavenger tip. In Fig. 6, an example of a piezoelectric bimorph with tip mass housed on a shaker is shown. By measuring the acceleration of the fixed base of the bimorph via the accelerometer and concurrently the displacement of its free end via the laser system, the typical transmissibility curves can be obtained [14]. Given a fixed excitation input, the resistive load is usually varied in order to obtain specific average output powers from the considered scavenger configuration. As depicted in Fig. 7, experimental results confirm that a trapezoidal geometry provides a higher specific output power, in good agreement with numerical results. The difference in terms of absolute values is due to a difference in the input acceleration: experimental specimens are not tested to their maximum limit to prevent damage. For the same reason, only the metallic layer is actually clamped.

Figure 6. Experimental setup: shaker, bimorph, and laser sensor.

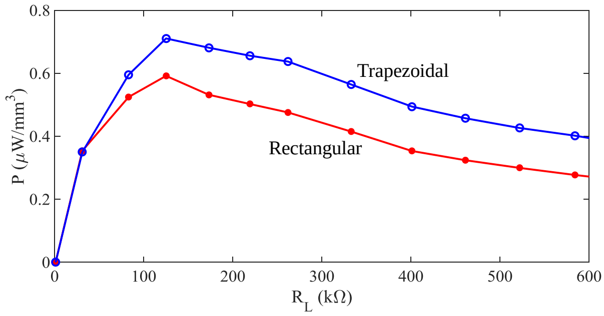

Figure 7. Experimental results in terms of specific power.

Since the optimum value of the resistive load is related to the first mode of resonance frequency [5], a decreasing trend over R_L is obtained here on the left part of Fig. 7.

C. Practical Application

Among all the different energy sources, human-generated power has been identified as particularly appropriate, especially for wearable systems that provide real-time continuous monitoring of some vital biometric parameters (e.g., acceleration, temperature, and blood pressure) in elder-care technology. Human-generated power is available in different forms: breathing, body heat, blood transport, arm motion, and walking. In particular, walking activity has been considered to be particularly promising; indeed, during walking, feet experience large deformations and stretching, as well as acceleration. Although walking is not a continuous activity, its power can thus be harvested and properly converted, providing an adequate energy source over time for wearable systems [6]. Piezoelectric vibrating bimorphs can be adopted for this purpose, exploiting the acceleration peaks that usually develop when the foot comes into contact with the ground at every gait cycle [2, 5].

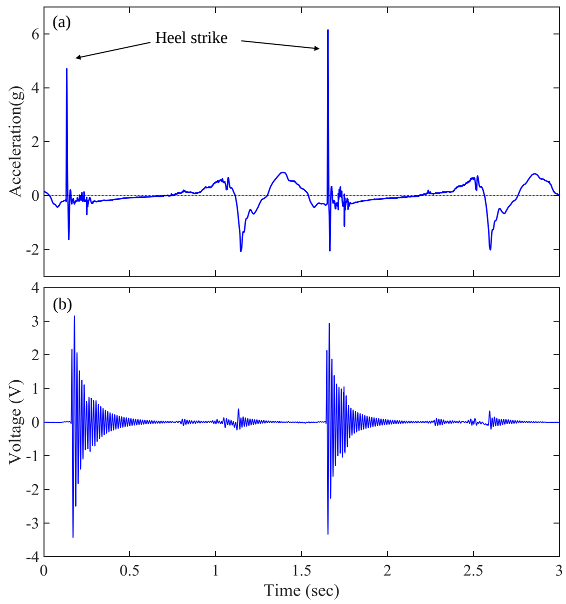

Figure 8. (a) Sample of measured heel acceleration signal during normal walking and (b) output voltage across bimorph excited by gait acceleration.

An example of a measured heel acceleration signal during normal walking is shown in Fig. 8(a). Two sharp positive/negative peaks during the contact phase can be observed, followed by smooth oscillations during the swing phase. Figure 9 shows a piezoelectric bimorph housed in a shoe with a customized clamping system aimed at maintaining the shoe comfort. The output voltage across the bimorph excited by the gait acceleration is depicted in Fig. 8(b). At every heel strike, the output voltage exhibits a classical damped response. As proposed in [5], starting from the reference rectangular configuration, a sensitivity analysis can be performed to individuate optimized geometries that maximize the electric power under the assigned acceleration input. Triangular-shaped bimorphs could be effective for this application not only because of their higher specific power, but also because the shoe heel can host a larger number of triangular harvesters compared to rectangular ones.

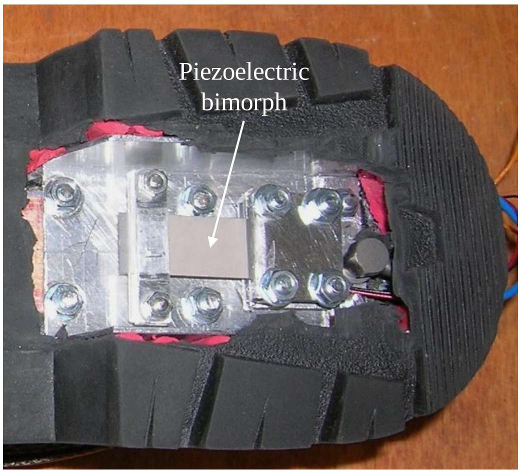

Figure 9. Customized clamp system with vibrating piezoelectric bimorph inside a shoe.

IV. Optimal Bending Deflection

The previous section discussed a way to increase the average strain by designing a piezoelectric bimorph with a nonconventional shape (trapezoidal). Being more difficult to be manufactured, these devices with a customized shape are yet more expensive than conventional rectangular bimorphs, easily available on the market. Another strategy to improve the average mechanical strain in the piezoelectric material is to force the piezoelectric bimorph to assume a predetermined optimized bending deformation, which is an approach that is particularly suited for nonvibrating loading. As already discussed in Section II, a cantilever beam develops a uniform and maximum average strain if it deforms at a constant curvature. Theoretically, this can be achieved by a constant bending moment applied at one end. From a practical point of view, though, it can also be obtained by forcing the beam to follow the shape of a cylindrical-shaped block, as sketched in Fig. 2(c). Two configurations are compared in the following: the "reference" configuration in which the piezoelectric bimorph is loaded by a tip force and can deform freely and the "enhanced" configuration obtained by imposing a constant curvature on the whole length of the bimorph. The value of the applied tip load is tuned so that both configurations reach at the clamped end the same amount of maximum stress (strain) on the piezoelectric material, considering the limit value suggested in [15].

A. *Numerical Simulations*

In [12], analytical models are developed to investigate the behavior of a piezoelectric bimorph forced to bend over a cylindrical-shaped block. Such analytical solutions are derived under plane stress or plane strain hypotheses and thus represent only two limiting cases of the actual 3D behavior of the bimorph, which is clearly more complex. It is a matter of fact that a plane stress condition arises at the lateral edges of the beam, as they are virtually stress-free. On the contrary, in the midsection (longitudinal symmetry plane), a condition close to plane strain is expected because of a certain degree of constrained strain along the transverse direction. Some transition between plane stress and plain strain condition is thus expected in the real beam. A 3D FEM, shown in Fig. 10, then allows for a more detailed analysis of the actual stress and strain distributions within the bimorph under bending. The model includes both the three-layer bimorph and the cylindrical-shaped block, with a frictionless contact between them. Only one-half of the structure is modeled to take advantage of symmetry. The layers are modeled as perfectly bonded by coupling the displacement values of common nodes at the interface. The piezoelectric material is modeled with eight-node solid elements with four degrees of freedom at each node (three components of mechanical displacement and the electric potential), with electromechanical coupling. The analysis simulates one single bending of the bimorph and the transient output voltage and the power discharge across a simple resistive load connected in series to the piezoelectric layers (the FEM adopts a circuit element suitable for piezoelectric-circuit analysis). A similar FEM is also used to study the reference configuration without optimized bending deformation. Some results, summarized in Table I, confirm the real advantage of using optimized bending to get an increased power level, which could be even four times greater.

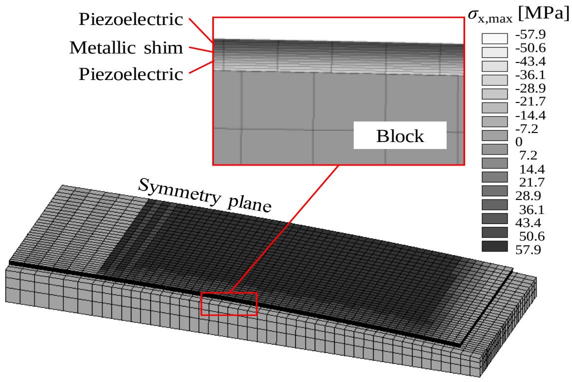

Figure 10. FEM of the bimorph in contact with the arc-shaped block and resultant distribution of bending stress.

TABLE I. PEAK VOLTAGE AND PEAK POWER OBTAINED FROM SIMULATIONS AND EXPERIMENTAL TESTS.

	FEM		Experimental	
	Reference	Enhanced	Reference	Enhanced
V (V)	45.9	120	8.6	21.1
P (mW)	14	96	0.5	3

B. *Experimental Measurements*

Experimental measurements are performed with the aim of confirming the numerical results observed in the previous section. The piezoelectric cantilever used in the experiments is a rectangular bimorph type V20W manufactured by MIDE Technology Corporation (Medford, MA, USA).

In order to test both the reference and the enhanced configurations, two different aluminum blocks are designed (Fig. 11). The reference configuration, which is loaded by a tip force and does not have a predetermined deformation, is replicated by designing a support block with a small step of fixed height at the clamp. The surface of the block underneath the beam is horizontal, and it allows the beam (clamped at one side) to freely deflect in the vertical direction under bending. The constant bending condition of the enhanced layout is obtained, instead, by designing a support block with a cylindrical surface. The beam, clamped at one end, is forced to assume a constant curvature up to complete contact with the lower block.

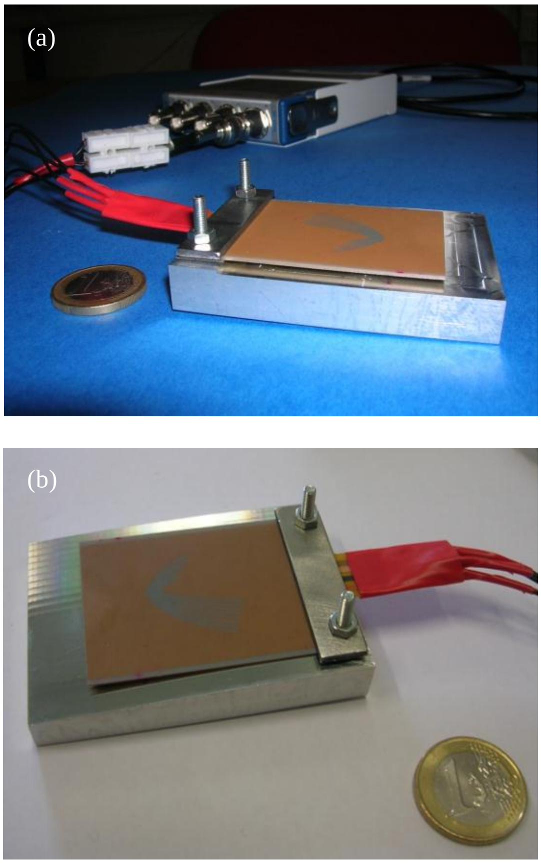

Figure 11. Experimental setup for the comparison between the (a) reference and (b) enhanced configurations.

The output voltage and dissipated power after one single bending imposed to the bimorph have been measured and compared for the two configurations, thus obtaining the two self-discharge curves depicted in Fig. 12. As predicted by numerical models, the experimental measurements also confirm that the enhanced configuration provides a higher output voltage compared to the reference configuration. Accordingly, the peak power supplied by the enhanced configuration is roughly five times higher than that of the reference layout (see Table I). It should be emphasized, however, that measurements on the commercial device cannot be directly compared with the results of numerical models: indeed, it was practically unfeasible to precisely model the MIDE bimorph used in experiments because of the lack of information on the exact thickness of piezoelectric/metallic layers, especially on the properties of internal glue and surface coating.

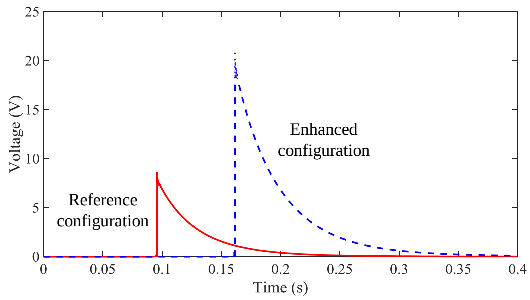

Figure 12. Self-discharge voltage curves after one single bending.

C. *Practical Application*

Although the results shown in Fig. 12 look promising, they actually refer to the output voltage after one single bending, which could be not very useful for practical applications. A system that can store the energy generated in repeated bending cycles should then be devised. A proper electric circuit (see the scheme in the top right of Fig. 13) can be designed to allow electric power storage after the more realistic situation of a sequence of multiple bending deflections. This configuration is particularly suitable also for supplying large amounts of energy at relatively delayed time instants. The circuit scheme is constituted by an alternating current–direct current (AC–DC) rectifier bridge connected to the bimorph electrodes and a capacitor, able to store the electrical energy for subsequent use to supply electrical devices or to recharge batteries. In the experiments, a simple resistive load was used to exemplify the electrical device that dissipates the generated power. The response of the bimorph connected to this circuit was firstly tested by applying multiple loads at different frequency rates. Since the mechanical response of the system was shown to never occur at resonance, the load rate does not influence the dynamic response of the bimorph. The energy storage and circuit response were, thus, somewhat insensible to the frequency of consecutive load cycles, which can be impulsive and also repeated at any desired rate. The proposed configuration can also be adopted to harvest energy from low-frequency loads, such as the inputs from human motion. In the tests, after several (10, 20, or 30) bending deflections imposed to the bimorph, a resistive load (calibrated to reduce as much as possible the time of power discharge) was connected to the electrical circuit and the power discharge curve was measured over time. The results obtained by adopting the enhanced configuration are shown in Fig. 13. As expected, the peak power (and hence the total amount of harvested energy) is approximately proportional to the number of loading deflections. A very small load is required for complete bending over the block. Therefore, in practical applications, even a small input load can produce a beam deflection and permits energy to be stored. This setup can, thus, store a relatively large amount of energy starting from a small input mechanical energy. Moreover, since no resonance vibration of the bimorph is required for optimal operation, any type of load can be used to produce energy. This makes the device a very effective energy scavenger.

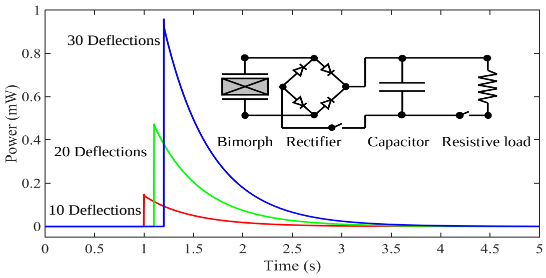

Figure 13. Power discharge curves after multiple bending deflections.

V. Conclusions

In this work, we investigated the possibility of increasing the electrical power delivered by classical rectangular piezoelectric bimorphs. The basic idea is related to the concept of uniform bending strain in beams. Better performances in terms of specific power per unit volume of piezoelectric material can be achieved, modifying the shape of the device. A triangular shape allows obtaining a uniform stress (strain) distribution along the cantilever surface, thus maximizing the electric power available. Another strategy to improve the average mechanical strain in the piezoelectric material is to force the piezoelectric bimorph to assume an optimized bending deformation. This strategy, particularly suited for nonvibrating loading, can be implemented by forcing the bimorph to follow the shape of a cylindrical-shaped block. The effectiveness of both strategies considered to improve the performances of piezoelectric scavengers is confirmed through numerical results and experimental measurements. The possibility of harvesting energy from low-frequency loads, as the inputs from human motion, can be thus pursued in a more effective way.

References

[1] S. R. Anton and H. A. Sodano, "A review of power harvesting using piezoelectric materials," *Smart Mater. Struct.*, vol. 16, no. 3, R1-R21, May 2007.

[2] D. Benasciutti and L. Moro, "Energy harvesting with vibrating shoe-mounted piezoelectric cantilevers," In *Advances in Energy Harvesting Methods*, N. Elvin and A. Erturk, Ed. 2013, pp. 141-162.

[3] F. Lu, H. P. Lee, and S. P. Lim, "Modeling and analysis of micro piezoelectric power generators for micro-electromechanical-systems applications," *Smart Mater. Struct.*, vol. 13, pp. 57-63. November 2003.

[4] L. Mateu and F. Moll, "Optimum piezoelectric bending beam structures for energy harvesting using shoe inserts," *J. Intel. Mat. Syst. Str.*, vol. 16, pp.835-845, October 2005.

[5] L. Moro and D. Benasciutti, "Harvested power and sensitivity analysis of vibrating shoe-mounted piezoelectric cantilevers," *Smart Mater. Struct.*, vol. 19, November 2010.

[6] N. Shenck and J. A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics," *Micro IEEE*, vol. 21, pp. 30-42, May 2001.

[7] D. Benasciutti, L. Moro, S. Zelenika, and E. Brusa, "Vibration energy scavenging via piezoelectric bimorphs of optimized shapes," *Microsyst. Technol.*, vol. 16, pp. 657-668, May 2010.

[8] D. Benasciutti, E. Brusa, L. Moro, and S. Zelenika, "Optimised piezoelectric energy scavengers for elder care," in *Proc. of European Soc. Precision Eng & Nanotech (EUSPEN) Conference*, 2008, pp.41-45.

[9] E. Brusa, S. Zelenika, L. Moro, and D. Benasciutti, "Analytical characterization and experimental validation of performances of piezoelectric vibration energy scavengers," in *Proc. SPIE Conference*, 2009.

[10] F Goldschmidtboeing and P. Woias, "Characterization of different beam shapes for piezoelectric energy harvesting," *J. Micromech. Microeng.*, vol. 18, September 2008.

[11] S. M. K. Tabatabaei, S. Behbahani, and P. Rajaeipour, "Multi-objective shape design optimization of piezoelectric energy harvester using artificial immune system," *Microsyst Technol.*, vol 22, pp. 2435-2446, October 2016.

[12] D. Benasciutti, L. Moro, and M. Gallina, "On The Optimal Bending Deflection of Piezoelectric Scavengers," *J. Intel. Mat. Syst. Str.*, vol 4, no. 5, pp. 627-639, March 2013.

[13] A. A. D. Brown, *Mechanical Springs (Engineering Design Guides)*. Oxford University Press, 1981.

[14] A. Erturk and D. J. Inman, "An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations," *Smart Mater. Struct.*, vol. 18, January 2009.

[15] M. Okayasu, G. Ozeki, and M. Mizuno, "Fatigue failure characteristics of lead zirconate titanate piezoelectric ceramics," *Journal of the European Ceramic Society*, vol. 30, pp. 713-725, February 2010.

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