euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Assessment of performances of optimized piezoelectric energy harvesters for wearables

Petar Gljušćić [1, 2] and Saša Zelenika [1, 2]

[1] *University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka, CROATIA*
[2] *University of Rijeka, Centre for Micro- and Nanosciences and Technologies, Radmile Matejčić 2, 51000 Rijeka, CROATIA*

sasa.zelenika@riteh.hr

Abstract
Wearable electronics, generally comprising low-power sensors, often aimed at Internet-of-Things solutions, can be powered by transforming low-level kinetic energy, induced by human motion, into electrical energy generated via piezoelectric energy harvesting principles. Such a design approach can lead to a significant increase of the autonomy of wearable devices. The main drawback in using piezoelectric energy harvesters is the narrow area of optimal operation around their eigenfrequency, which, due to the random nature of human motion, is particularly noticeable in wearable applications. In order to deal with this challenge, in this work the conventional rectangular bimorph cantilever is hence segmented into optimized shapes that allow achieving an increased specific power output and an adaptation to the foreseen applications, whereas the frequency up-conversion principle is employed. A complex coupled-field finite element model is used to simulate the electromechanical response of the resulting harvesters' designs, and experimental measurements, on a suitably developed experimental set-up, are performed. A wrist-worn kinetic energy harvesting solution is hence proposed, combining the mentioned approaches. It is primarily aimed at powering ultra-low power wearable devices for medical applications, e.g. telemedicine, drug delivery and health monitoring.

Kinetic energy harvesting, broadband piezoelectric energy harvesting, wearable technology, biomedicine, miniaturized devices

1. Energy harvesting and wearable technology

In recent times, for gadgets and Internet-of-Things (IoT) components, a trend towards rapid miniaturization, as well as increased power autonomy, can be observed. A very interesting feature in this framework is the possibility of such devices to be worn by the users as an accessory (e.g. a watch) or a clothing element. Such devices, also known as wearables, can comprise different sensors, widely broadening their field of application. One of the niches where wearables could have a noticeable impact, is the field of telemedicine, which involves remotely monitoring patients' states by using the existing telecommunications infrastructure. This may include monitoring of patients' heart rates, blood pressure, blood sugar levels or even employing drug delivery systems [1].

Wearable devices require a wearable power source as well. Apart from the conventional battery, characterised by several shortcomings, a suitable power source for such devices could be the body itself, i.e., they can rely on energy harvesting principles. The chosen energy harvesting approach largely depends in this frame on the energy form, e.g. photovoltaic modules can be used for harvesting solar energy, thermoelectric generators are used for thermal energy sources, whereas kinetic energy, induced by the motion of living beings or machinery, can be collected by using piezoelectric or electromagnetic devices [2, 3]. The possible application of piezoelectric energy harvesters, in the form of bimorph cantilevers, is considered in this this work as a viable power source for wearable devices in medical applications.

2. Broadband piezoelectric energy harvesting

The main issue when using piezoelectric bimorphs as energy harvesters, is the narrow area of optimal operation around the eigenfrequencies of a specific device. In this area, a high voltage level is generated, but it rapidly decreases with even a slight variation of the excitation frequency [2]. On the other hand, when collecting kinetic energy from human motion, the excitation varies across a wide range of frequencies, thus reducing the possible power outputs of the harvester. Several approaches to solve this problem, i.e., to achieve the broadening of the optimal frequency spectrum, have recently been suggested, the most promising being:

- changing the conditions around the cantilever free end (e.g. damping control or active tuning),
- changing the geometry of the cantilever (by using complex geometries with bi-stable or nonlinear responses, or a large number of differently tuned cantilevers) [2, 3], or
- frequency-up conversion, i.e., "plucking" the free end of a cantilever and letting it oscillate at its eigenfrequency [4].

A novel combination of design configuration variants given by geometric variations, while exciting the harvesters by using frequency-up conversion, is considered in this work.

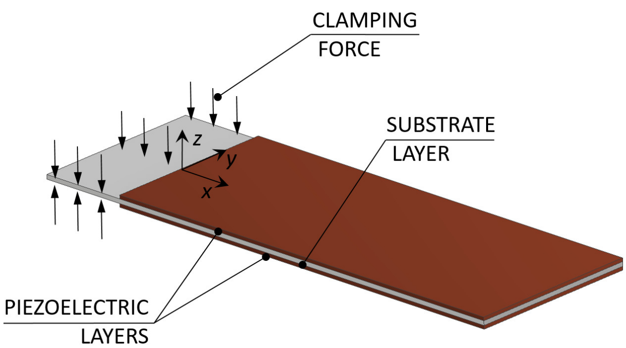

Figure 1. Scheme of the studied energy harvesters.

2.1. *Influence of harvester's geometry and modelling of the device*

In order to comply with the realistic case, as well as to avoid the potential damage of the piezoelectric layers due to stress concentrations [1], all studied design configurations are assumed to be clamped on the steel substrate of the piezoelectric bimorph, as shown in Figure 1. What is more, in the initial analyses no tip mass is considered at the free end of the harvesters, thus simplifying the needed simulations and reducing their number. This allows focusing the work on the influence of the geometry of the harvester on its dynamical electromechanical response, whereas the considerations on an optimised tip mass for each harvester's shape configuration, allowing to increase further the obtainable specific powers, will be performed in future work.

In the conventional rectangular bimorph piezoelectric energy harvesters (cf. Figure 2 – variant A), the bending moment, which causes the mechanical stress and, therefore, the generation of charge in the piezoelectric layers, decreases linearly towards the free end of the cantilever. As it is well known, by modifying the bimorph to an optimized triangular shape, a uniform stress distribution along the surface of the cantilever can be achieved. When the clamping and the usual tip mass location at the free end are taken into account, the triangular shape can be approximated with a trapezoidal one. It has been shown that the specific power outputs of piezoelectric energy harvesters can be significantly increased by using such trapezoidal shapes. What is more, by inverting the trapezoidal shape, i.e., by clamping the cantilever at the narrow end of the harvester, so as to induce a marked stress increase near the fixation, while placing the tip mass on the wider end, an even more pronounced growth in specific power is achieved [5].

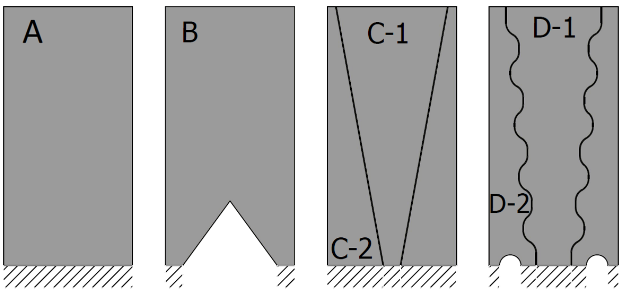

Figure 2. Shape variations aimed at the increase of compliance.

To enable the optimization of different cantilever configurations, having as goal the maximization of the obtainable power output levels, while concurrently overcoming the limitations of the analytical CMEDM approach [6], a suitable numerical (FEM) model, comprising modal and coupled harmonic analyses, is thus developed in ANSYS® [1]. The variation of cantilever shapes can hence be studied, while all analysed cantilevers are constrained in the same dimensional envelope (30 mm x 15 mm) and have the same layers' thicknesses (substrate: 0.1 mm, PZT: 0.2 mm). The addition of notches (or similar shape variations), increasing cantilever's compliance, thus inducing a boosting of charge generation, with the resulting increase of the power outputs, is thus considered. The first analysed design configuration variant includes, hence, adding a V shaped notch at the clamped end of a rectangular cantilever (variant B in Figure 1). The second one (designated as design configuration C) consists, in turn, in segmenting the cantilever in an inverse trapezoidal and two half-trapezoidal shapes, while the third one is based on adding a wavy edge on the segmented cantilevers (design variant D). Multiple numerical analyses, aimed at obtaining the optimal load resistances (R_L), i.e., those where the output voltages and powers are maximal for each harvester's shape and segment, are thus performed. The respective clamping points for each considered design configuration are marked again in Figure 2 for clarity purposes according to the boundary condition set in Figure 1.

The benefits of using the segmented design configurations can be boosted by using a frequency up-conversion principle of plucking the free end of the cantilevers [1]. Several excitation concepts are being considered and developed from the mechanical engineering design point of view in this frame, all based on a watch-like device, as shown on Figure 3 [7], where a rotating flywheel converts the random kinetic energy generated from human motion into rotational motion. The latter is then used to "pluck" the cantilever segments, inducing the oscillatory excitation of the piezoelectric harvesters at their eigenfrequency, thus decoupling their response from the evidenced problems and generating electrical energy in the optimal dynamical conditions [8]. Such watch-like devices, being developed in collaboration with medical institutions, can comprise one (Figure 3a) or multiple (Figure 3b) segmented piezoelectric cantilevers, thus increasing energy density. The produced electrical energy can thus be used to operate low-power sensors, aimed at biomedical applications or IoT solutions.

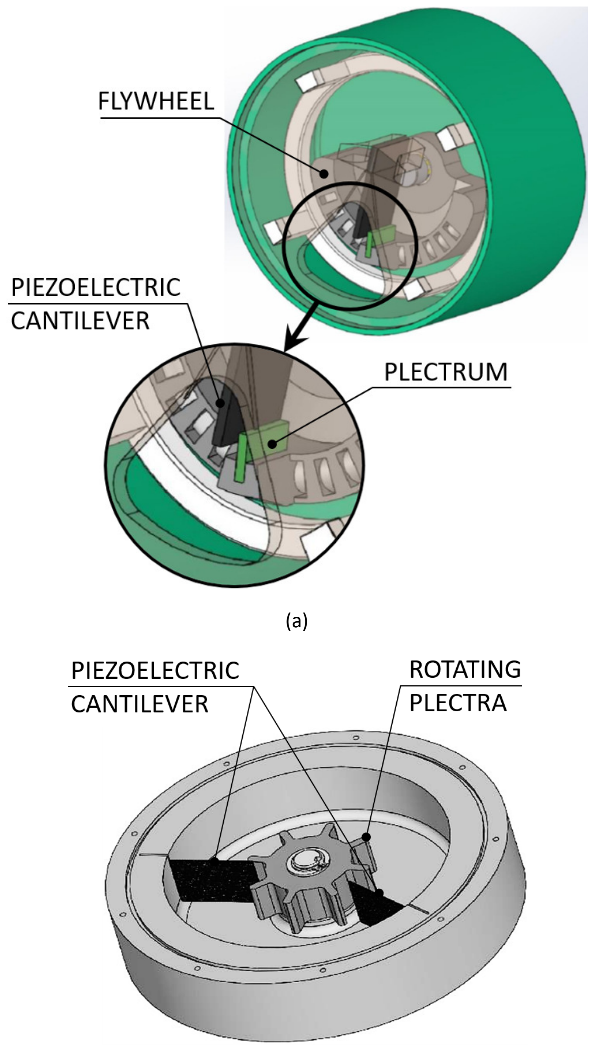

Figure 3. Design concepts of a watch-like wearable energy harvesting device: with a single (a), and with multiple cantilevers (b) [7].

2.2. Results

The specific power outputs of the studied harvester shapes are obtained numerically from the output voltages and optimal load resistances, and, given the constant layers' thickness, normalized over the surface of the harvesters.

Figure 4 shows the thus obtained specific power outputs for each considered shape and segment. A clear increase can thus be observed for shapes with added notches, i.e., with increased compliance. What is more, an expected eigenfrequency shift towards lower values can also be noticed. Considering the respective numerical data reported in Table 1, a slight change of the optimal load resistance values can be observed for the segmented shapes C and D of Figure 2, that is not noticeable for the design configurations A and B; the latter could be due to a larger increment step of load resistances used in the respective numerical sweeps. A further increase in specific power outputs is expected when the optimized tip mass (i.e., that inducing the maximal oscillating deflections compliant with the fatigue strength of the piezoelectric material) is introduced, resulting in larger vibrational bending of the energy harvesters. Thins will, obviously, imply the need to iteratively calculate again the dynamic response of the harvesters as well.

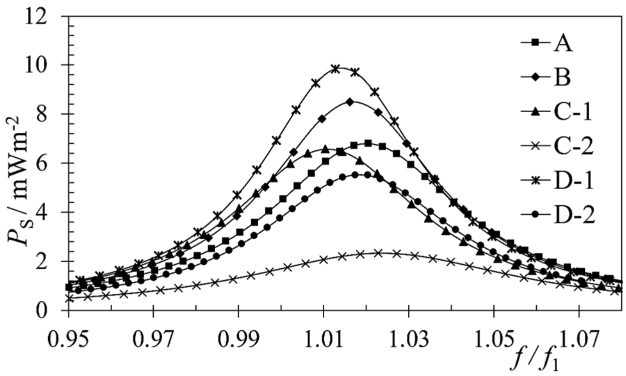

Figure 4. Numerically calculated specific power outputs for multiple cantilever shapes.

Table 1 Results of FEM analyses for multiple cantilever shapes.

	A	B	C-1	C-2	D-1	D-2
f_1/Hz	239	210	123	375	173	271
R_L/kΩ	10	10	35	25	25	35
P_{Smax}/mW/m^2	6.8	8.5	6.6	2.3	9.8	5.5

3. Conclusions and outlook

Based on the initial study of the possibility to increase the power outputs of piezoelectric energy harvesters for wearable applications by varying their design configurations, it can be concluded that novel harvester shapes with increased compliance could provide the means of significantly improving their performances. There is also a clear indication that, by increasing the compliance of already optimized (segmented) shapes, a further improvement could be achieved, while segmented configurations provide means of a versatile adaptation of the performances of each segment to multivariate loads (different sensors). Additional analyses are being carried on to determine the optimal tip masses for the analysed shapes.

On the other hand, the experimental validation of the attained results is being performed. A plucking frequency up-conversion experimental set-up, comprising a controllable rotational exciter (1), a variable resistance box (2), an oscilloscope for monitoring and acquiring the output voltage levels (3), and a laser Doppler vibrometer for monitoring the dynamical response of the studied harvesters (4), has thus been developed (Figure 5).

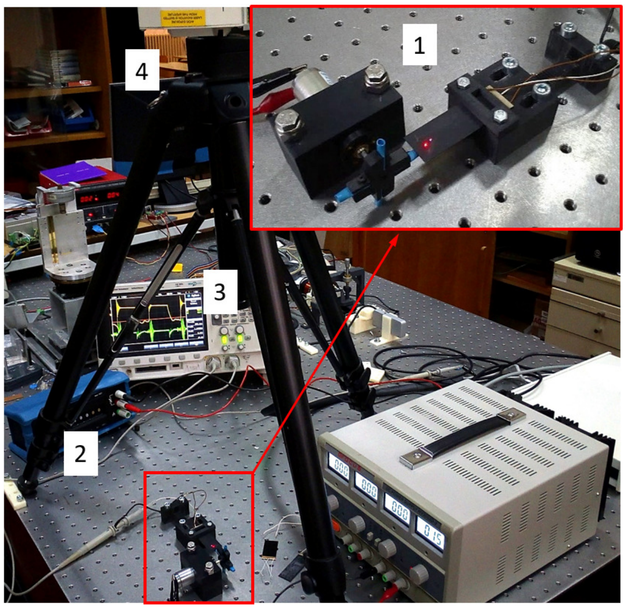

Figure 5. Experimental set-up for frequency up-conversion analyses.

A closed-up view of the experimental setup, shown in Figure 6, allows evidencing better the core elements of the set-up. It can thus be seen that the analysed piezoelectric energy harvester (5) is clamped to an adjustable clamping mechanism (6), enabling a precise positioning of the cantilever in relation to the excitation plectra (7). The rotational plectrum holder (8) is then coupled to a DC motor, enabling the variation of plucking frequency as well as of the direction of rotation.

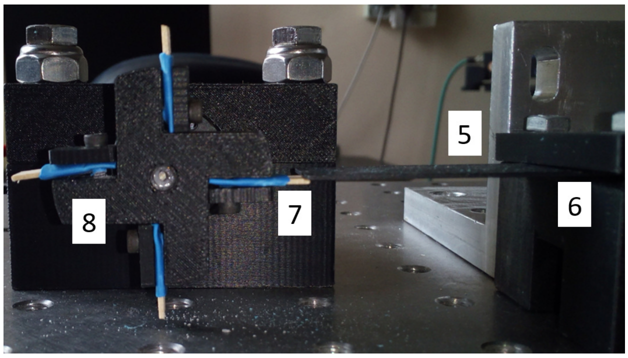

Figure 6. Detail of the frequency up-conversion “plucking” mechanism.

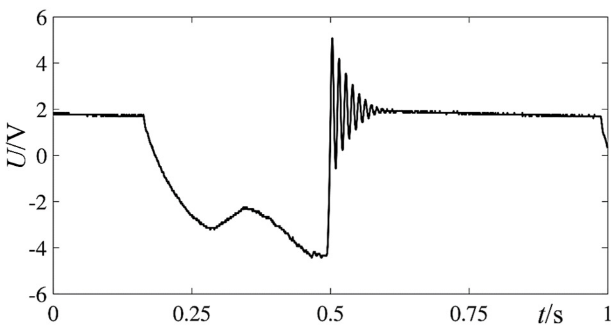

Figure 7. Voltage output for a rectangular plucked harvester.

As part of the iterative process of developing an adequate model and a suitable experimental configuration for the studied system, experimental measurements, aimed at analysing the effect of plucking intensity and frequency on the response of the harvesters, are thus currently under way. The influence of both plucking frequency and plectrum stiffness are analysed, as is the clamping of the plectrum itself and the direction of rotation.

Several plectrum materials are therefore being studied, ranging from metal, to wood and various polymers.

Preliminary results (shown in Fig. 7) allow evidencing a significant dynamical effect of the impact of the plectrum on the harvester on the electromechanical response of the latter. This adds an even higher level of complexity to the task related to the adequate numerical modelling of the studied energy harvesting devices.

In any case it is shown that the combined improvements of the two described piezoelectric energy harvester's design approaches, namely the cantilever segmentation and the employment of the frequency up-conversion, have a marked potential in the development of a new class of optimised piezoelectric energy harvesters aimed at converting the random kinetic energy excitation, generated by human motion, into electric energy to be used for successfully powering various sensors. What is more, the proposed design approach allows anticipating the development of hybrid systems where piezoelectric energy harvesting could be synergistically coupled to energy harvesting technologies based on different energy sources, such as thermoelectric, RF or photovoltaic energy, further increasing the overall efficiency of the end product as well as its autonomy.

Such harvesters, coupled to a carefully designed power management system and a cautious approach to privacy and data protection [1], could enable the development of a new class of autonomous wearable devices suitable to be used as biomedical sensors for remote patients' monitoring, in industry 4.0 applications as workers' health and safety monitors, for monitoring training achievements of sportsmen, as well as for multiple IoT applications.

Acknowledgements

Work supported by the University of Rijeka uniri-tehnic-18-32 grant "Advanced mechatronics devices for smart technological solutions", by using the equipment funded via the EU European Regional Development Fund (ERDF) project no. RC.2.2.06-0001 "Research Infrastructure for Campus-based Laboratories at the University of Rijeka (RISK)" and partially performed in the framework of the COST Action CA18203 "Optimizing Design for Inspection".

References

[1] Gljušćić P, Zelenika S, Blažević, D and Kamenar E 2019 *Sensors* **19** 4922

[2] Prya S and Inman D 2009 *Energy harvesting technologies* (Springer)

[3] Kaźmierski T J and Beeby S 2011 *Energy harvesting systems principles, modeling and applications* (Springer)

[4] Kuang Y and Zhu M 2017 *Sensor Actuat A-Phys* **263** 510–20

[5] Benasciutti D, Moro L, Zelenika S and Brusa E 2010 *Microsyst Technol* **16**(5) 657–68

[6] Erturk A and Inman D J 2009 *Smart Mater Struct* **18** 025009

[7] Gljušćić P, Zelenika S and Franulović M 2019 *36th Danubia-Adria Symp Adv Exp Mech* (Plzeň, Czech Republic: Uni West Bohemia) pp 17-8

[8] Halim M A, Xue T, Rantz R, Zhang Q, Gu L, Yang K and Roundy S 2019 *J Phys: Conf Ser* 1407 012003