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

Energy harvesting for wearable applications

[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

Abstract

Energy harvesting, the process of collecting low level ambient energy and converting it into electrical energy, is a promising approach to power wearable devices. By converting the energy of the human body by using piezoelectric and thermoelectric principles, the need for batteries and charging can be avoided, and the autonomy of wearable devices can be significantly increased. Due to the inherent random nature of human motion, however, the energy harvesting devices need to be specifically designed in order to ensure their optimal operation and sufficient power generation. Using several combined approaches, a new class of autonomous devices, suitable for telemedicine, patient monitoring or IoT applications, can be developed.

Keywords: *wearable technologies, energy harvesting, broadband piezoelectric devices, geometry optimization, frequency up-conversion, thermoelectric energy harvesting*

1. Introduction

Energy harvesting (EH) - the process of collecting low-level ambient energy and its conversion into electrical energy, is an increasingly studied approach to reduce or eliminate battery usage in various devices, resulting in the potential development of novel autonomous systems. The generally considered forms of available ambient energy are kinetic (vibrations), thermal (waste heat), solar and radio frequency (RF) sources. An ubiquitous energy source is certainly kinetic energy, present in all moving systems, which can thus be collected and converted into electrical energy by using various technologies, the most common being piezoelectric and electromagnetic transducers [1-2]. The generally used form of piezoelectric transducers are bimorph cantilevers, in the design configuration shown in Figure 1, comprising two piezoelectric layers on a metallic substrate, clamped at the end subject to external dynamical excitations. The tip mass on the free end serves, in turn, as a deflection amplifier and for tuning the response of the device to a specific excitation frequency [3].

2. Wearable technologies

The term wearable technologies (or wearables) usually encompasses a range of devices, generally sensors, with data acquisition, processing and transmission components (Figure 2) [3], that can be worn as a typical accessory (e.g. a wrist watch, smartphone or as part of clothing), and used for a variety of purposes, from health monitors (blood pressure, heart rate, blood glucose levels), to automated drug (e.g. insulin) delivery systems.

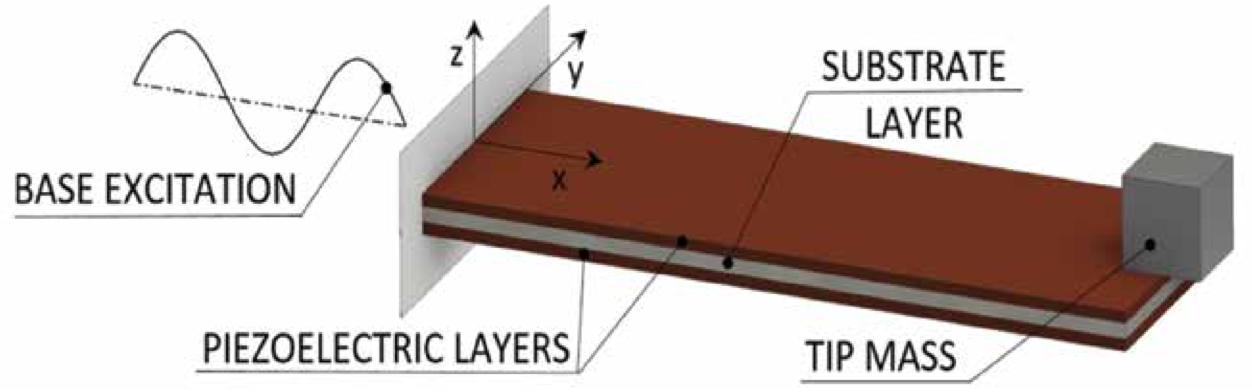


Fig. 1. Bimorph piezoelectric energy harvester [3]

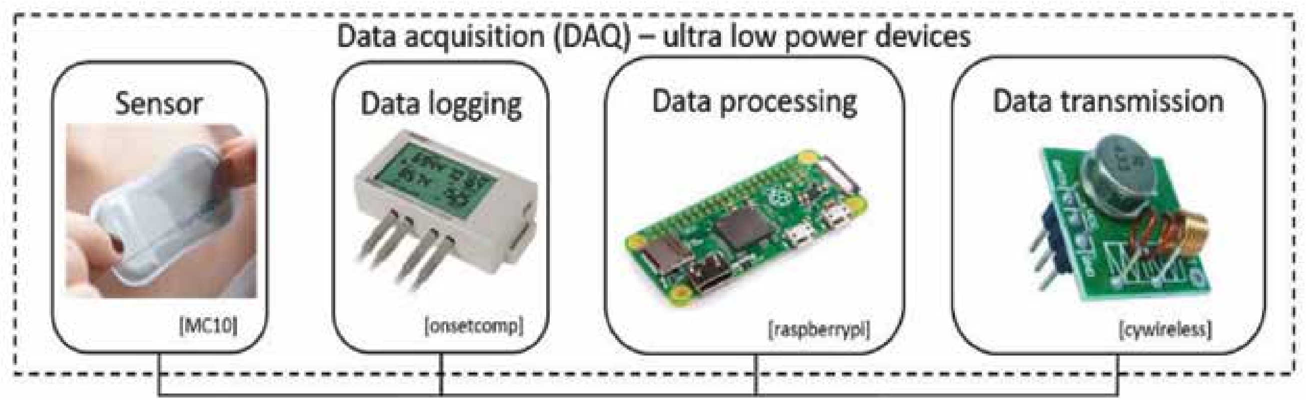


Fig. 2. Components of a typical wearable system

As all electronic devices, in order to operate, wearables require electrical energy, usually supplied by a battery, which needs to be replaced or recharged, causing a negative environmental impact and reducing the autonomy of the devices – which is especially important in telemedicine, when wearables are used in remote patient monitoring. The power requirements of typical wearable device components have been thoroughly analysed in literature, allowing to conclude that the sensors generally require relatively low power levels (from tens of µW up to a couple of mW), while other components, including data processing and transmission components, can often necessitate larger power levels [3-4]. This issue can be resolved by reducing the active time of such components, e.g. by minimizing the data transfer intervals, according to appropriate medical practices [3].

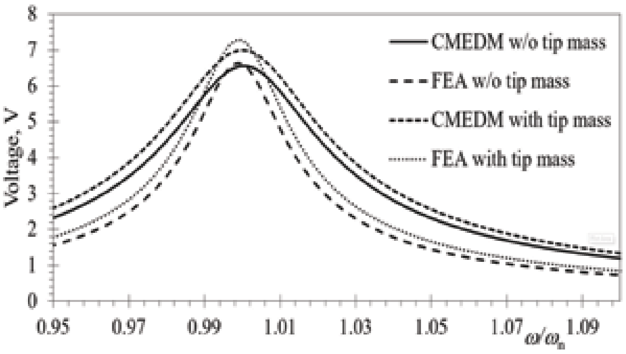


Fig. 3. Electromechanical response of a rectangular bimorph PEH [3]

On the other hand, the human body produces significant amounts of energy, the most promising being the energy of human motion, e.g. arm movement or walking/running, with available power levels up to ~ 60 W [5]. A conventional power source for wearables can, thus, be replaced by an EH system positioned on the body, such as the described piezoelectric energy harvester (PEH), hence enabling a novel class of autonomous wearable devices that do not require battery recharging or replacement.

3. Issues with PEHs in wearable technologies

A major issue inherent to bimorph PEHs is their narrow area of optimal operation around the eigenfrequency of a specific device (Figure 3), with a significant drop in output voltages and powers as soon as the base excitation drifts away from the eigenfrequency [3].

This issue is particularly evident when PEHs are employed in wearable technologies. In fact, the excitation generated by human motion results in random vibrations. Figure 4 shows thus the EH voltage output for devices excited by random human motion such as walking, measured in the wrist and head areas [6]. In such cases it is difficult or even impossible to properly tune the PEH to ensure its optimal operation.

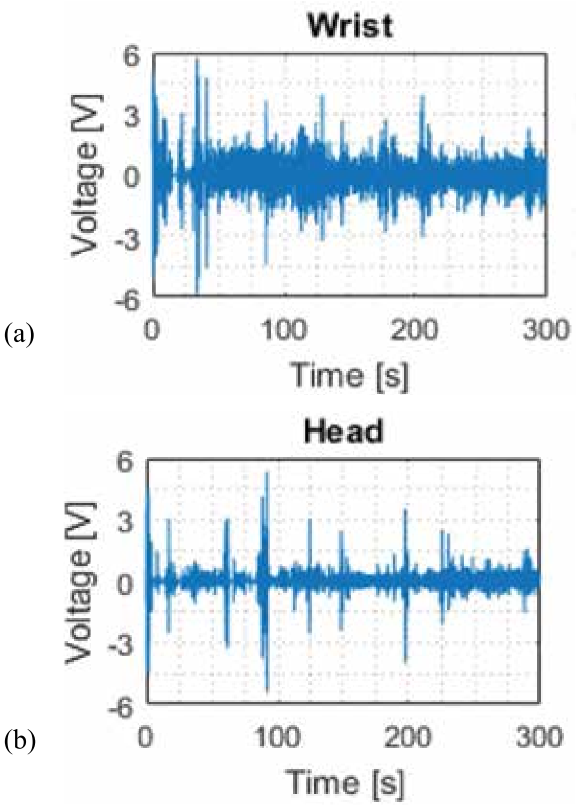


Fig. 4. Examples of random human motion excitations by walking measured in the wrist (a) and head (b) areas [6]

Several methods of widening the optimal spectrum of PEH operation, and thus overcome the above described issue, have been proposed in literature. Those considered as the most promising ones are [3, 7]:

- changing the conditions around the free end of the PEH (e.g. via active tuning or damping control);
- changing the cantilever geometry (e.g. by using several differently tuned PEHs, via complex geometries or by resorting to bi-stabile nonlinear responses);
- frequency up-conversion (FUC) mechanisms (i.e., by plucking the PEH's free end and letting it oscillate at its eigenfrequency).

The focus of our work is to analyse the influence of the geometry on PEH's response, and to find a way to combine a geometry change approach with a FUC mechanism, so as to achieve optimal operation even with random excitations generated by human movements.

To be able to accurately simulate the behaviour of the resulting devices, a suitable model is needed. Although several mathematical models that describe the PEH response do exist, the most accurate was proven to be the recently developed "coupled modal electromechanical distributed parameter model" (CMEDM) [8]. Although this model allows overcoming many disadvantages of prior models, it is still limited to a cantilever with a constant rectangular cross-section. In order to analyse the effects of a geometry variation on PEHs' response, a more flexible yet complex finite element (FE) numerical model is thus developed using ANSYS® [3]. The FE model comprises three separate analyses:

- **modal analysis:** determination of the mechanical dynamical response and the respective eigenfrequencies;
- **coupled harmonic analysis:** determination of the coupled electromechanical dynamical responses;
- **coupled transient analysis:** linear and nonlinear (including geometrical nonlinearities) determination of dynamical responses under forced excitation in discrete time steps.

3.1. Modal analysis

The initial step of the FE modelling process is the modal analysis, validated by comparison with CMEDM. This step is needed to determine the eigenfrequencies of the PEH. In the herein considered case, only the first modal shape is considered, since the largest deflections, and hence the highest output voltages, are achieved in this state. Within this step only the purely mechanical response of the PEH is observed, while the piezoelectric properties of the material are set to zero. The performed mesh sensitivity analysis allowed then concluding that it has a negligible influence on the calculated eigenfrequency. A coarser mesh can thus be used in the subsequent FE analyses, reducing the required processing power requirements and analysis times [3].

3.2. Coupled harmonic analysis

After the initial modal analysis, several coupled harmonic analyses are performed in order to determine the coupled dynamical electromechanical responses (coupled FRFs) of the considered PEH. The harmonic excitation bandwidth of the fixture is thus set around the eigenfrequency value determined via the modal analysis, while the other boundary conditions remain unchanged. In order to simulate a resistive load, enable output voltage estimation, and calculate PEH's output power, a variable resistor element is then introduced into the model between the charge collecting points [3].

A major requirement needed to obtain accurate results of harmonic analyses is the definition of damping. Rayleigh damping, commonly used in FE analyses, is therefore calculated based on the experimentally attained damping coefficients ζ. By performing several harmonic analyses while varying the excitation frequencies and the attached load resistances (from the Ω up to the MΩ range), coupled harmonic responses are obtained, allowing to determine the optimal resistance value, i.e., that where the highest output voltage is achieved [3].

3.3. Coupled transient analysis

Linear and nonlinear coupled transient analyses are performed next to attain the dynamical responses of the PEH subjected to forced excitation in precisely defined discrete time increments. A sinusoidal excitation profile is hence introduced and applied to the clamped base, while the PEH geometry and the boundary conditions remain identical to those in the harmonic analysis. With the occurrence of large deflections, nonlinear effects become more relevant, so that the responses can no longer be predicted by the assumptions of the linearized Euler-Bernoulli model, and a nonlinear transient analysis has to be used (Figure 5) [3].

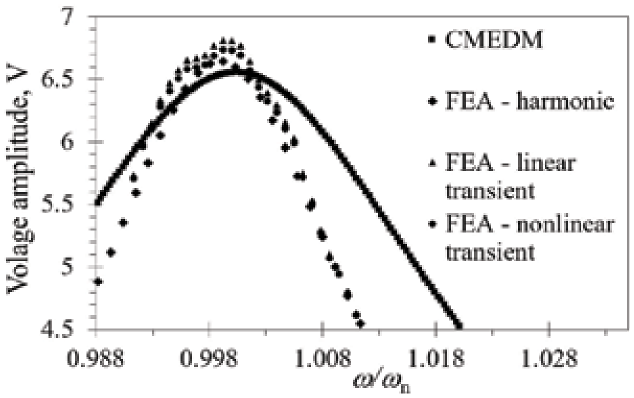


Fig. 5. Linear and nonlinear FEA transient responses for a rectangular PEH [3]

4. Influence of geometry on PEH response

By means of FE analyses as well as experimental measurements, it has recently been demonstrated that by changing the geometry of a conventional rectangular PEH to an optimized trapezoidal shape, the specific power output of the considered EH device can be significantly increased. A further increase was then achieved by clamping the trapezoidal PEH at its narrow end, i.e., when an inverse trapezoidal shape is used [9].

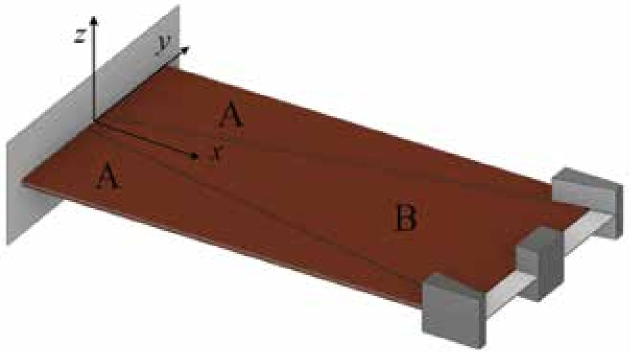


Fig. 6. Segmented PEH geometry [10]

Due to a limited available volume (i.e., limited PEH surface area) inherent to wearable devices, a conventional rectangular PEH shape (indicated with R) of a predefined surface area can thus be segmented, as shown in Figure 6. Two trapezoidal (A) and one inverse trapezoidal shape (B) are thus attained, potentially resulting in an increase of the specific power outputs, while keeping the surface area (and volume) unchanged. The respective voltage and power output values are hence calculated by performing several FE analyses for each segment of the resulting design configuration, while varying the respective load resistances. The obtained specific power output values, normalized w.r.t. the surface areas, are depicted in Figure 7, where a significant specific power increase of the segmented PEHs can be observed [3, 10].

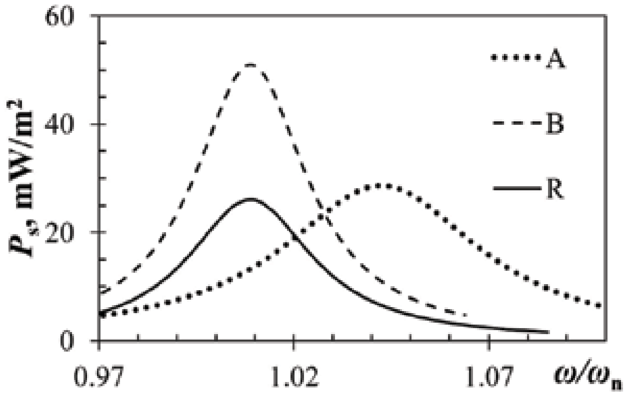


Fig. 7. Comparison of specific power outputs of rectangular and segmented PEHs [10]

The power output of PEHs can be further increased by introducing various stress concentrators in the form of notches and waves into the geometries. Two different approaches are being studied in this frame, one with a V-notch at the base of a rectangular PEH (indicated now in Figure 8 as, respectively, design configurations A and B), while the other one comprises a wavy edge on a segmented PEH (indicated as designs C and D). [11].

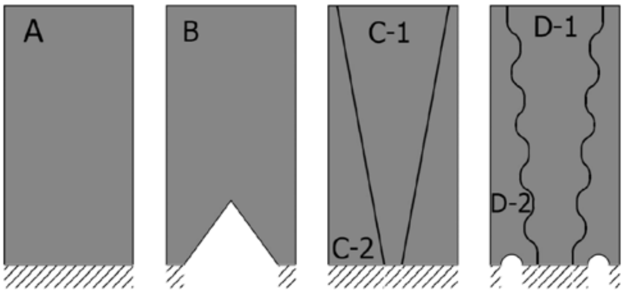


Fig. 8. Increasing PEH power output by introducing stress concentrators [11]

Multiple FE analyses with the attainment of an optimal resistance value for each variant of the PEH design are performed, allowing the output voltages and the respective specific power outputs to be calculated. A noticeable increase in specific powers is thus obtained for the shapes where stress concentrators are introduced (Figure 9) [11].

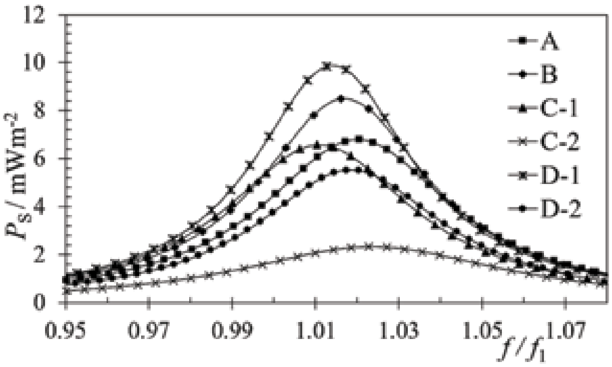


Fig. 9. Specific power outputs for PEHs with added stress concentrators [11]

5. Frequency up-conversion mechanisms

Frequency up-conversion mechanisms are aimed at converting random ambient excitations into a periodic excitation of the PEH. This is achieved by plucking or impacting the cantilever free end and letting the device oscillate at its eigenfrequency. Such configurations thus operate always in optimal conditions, hence overcoming the previously evidenced drawbacks. This approach, combined with a flywheel that converts random kinetic energy from human movements into rotational motion, results then in a system suitable for a wrist watch-like device (Figure 10). The flywheel has a plectrum attached to it and, while rotating, plucks the free end of the PEH.

Such devices, being developed in collaboration with medical institutions, can then comprise one or multiple segmented PEHs, reducing the volume required for power generation, increasing power outputs and, thus, the autonomy of the device [11].

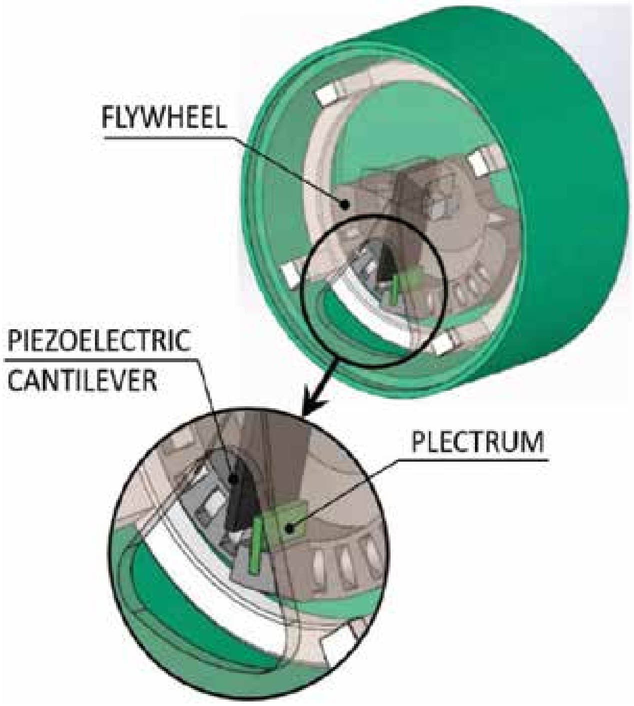


Fig. 10. Wearable watch-like device using a FUC principle [11]

Various effects on the response of a plucked PEH are being evaluated in an ongoing experiment. The studied parameters include the speed and direction of plectrum rotation, i.e., the velocity and direction of the approaching plectrum, as well as the influence of the material properties of the plectrum itself on the PEH response. The respective experimental setup, shown in Figure 11, comprises thus an adjustable clamping base, suitable for the analysis of different PEH sizes, as well as a controllable electric motor with an attached plectrum holder, allowing a quick change of different plectra [11].

A preliminary electromechanical response of a plucked PEH is shown in Figure 12, where the initial cantilever deflection due to the plucking of the free end, as well as the free oscillation of the PEH, can be well observed.

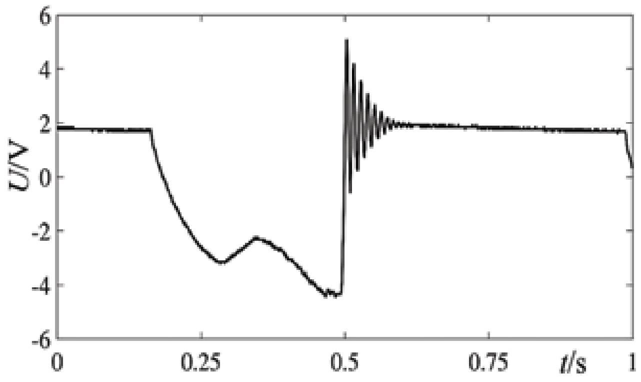


Fig. 12. Electromechanical response of a plucked PEH [11]

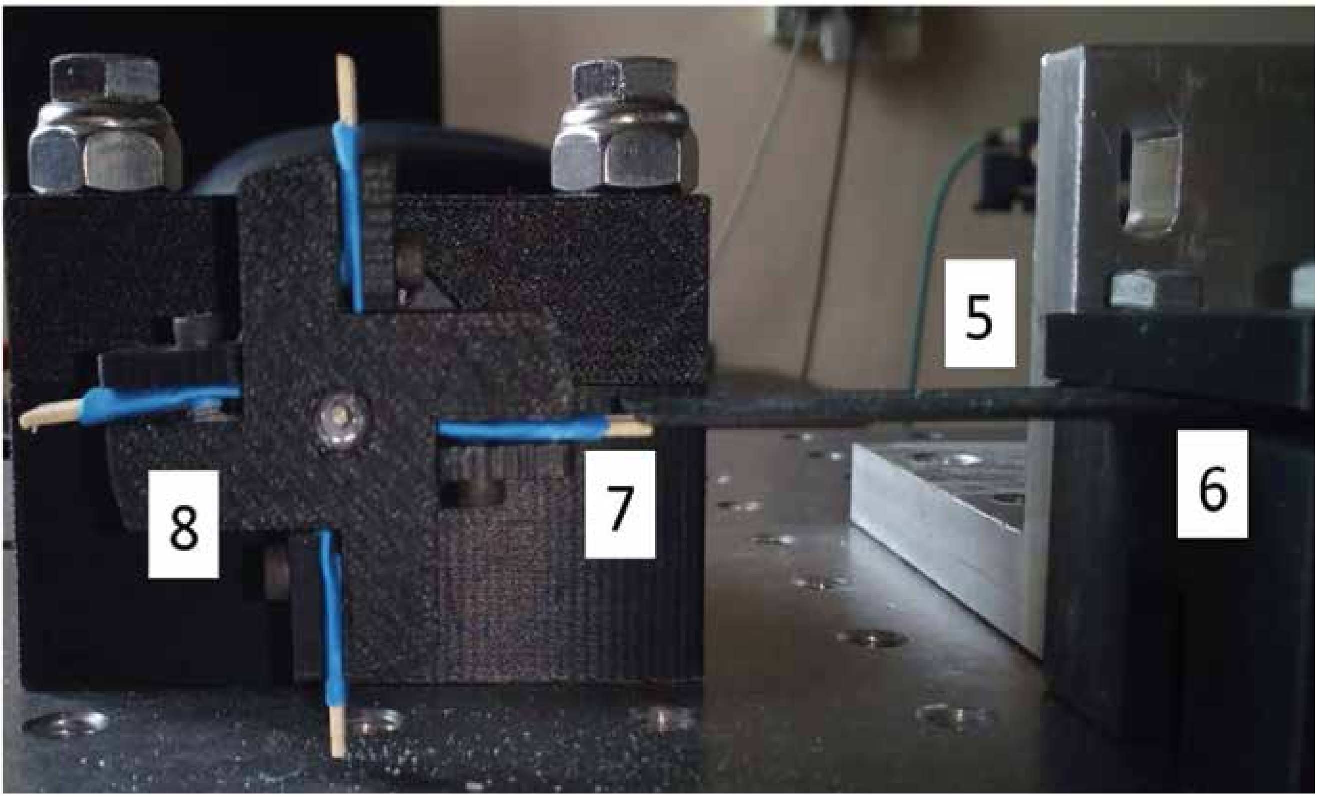
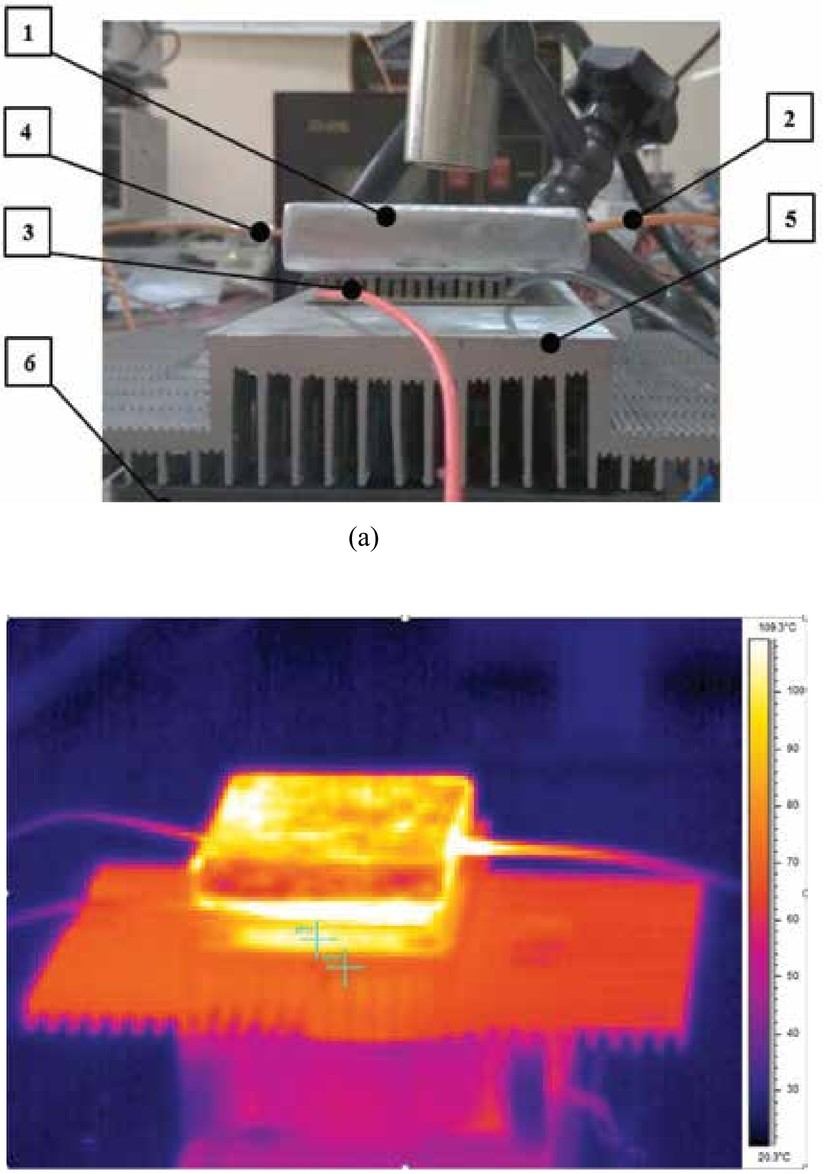


Fig. 11. Frequency up-conversion experimental setup [11]

6. Thermoelectric energy harvesting

Another form of ambient energy available on the human body is waste heat, emitted due to metabolism. Such energy form, i.e., the temperature gradient between the surface of the skin and the surrounding air, can be converted into electrical energy by using a solid state device based on the Seebeck effect, referred to as the thermoelectric generator (TEG - Figure 13) [12].



(a)

(b)

Fig. 13. TEG as part of an experiment (a), and respective thermal imaging (b) [12]

The main issue with TEGs is their low energy conversion efficiency that decreases with reduced temperature differences. This drawback is, however, at least partially compensated by the simplicity of this type of EH devices, having no moving parts. TEGs can enable also a simple and effective addition to an existing EH system, thus creating a novel hybrid system with extended autonomy, suitable for utilization in wearable technologies.

7. Power management in wearable EH systems

When multiple or segmented PEHs are used, or when different EH devices (e.g. PEGs and TEGs) are concurrently employed, thus creating a hybrid EH system, a suitable power management scheme is needed. In fact, the energy harvested by such systems needs to be properly managed to obtain a smooth and stabilized voltage supply that can be used to power the considered load (various sensors as well as data processing and communication components) [3].

In cases when an energy surplus is produced by the EH system, the task of the hence employed circuitry is also to manage this surplus and store it using a storage element such as a supercapacitor or a rechargeable battery, so that it can be used when it is needed by the wearable device components. The introduction of a storage element allows for short power bursts, which could be useful in time periods when a higher amount of power is needed, e.g. for data transmission [3].

An example of a power management scheme, aimed at managing multiple power inputs as well as to store surplus energy for later use, is shown in Figure 14. The central component of the power management electronics is a DC-to-DC buck converter that enables the collection of low-level energy onto a storage device (capacitor) on the primary side, and transferring it to the secondary side when the levels are high enough to power the wearable components or to charge the main storage element [3].

8. Conclusions and outlook

Energy harvesting is a viable approach to power wearable devices by using energy from the human body in the form of kinetic energy of human motion and/or emitted body heat. Innovative solutions, such as the segmentation of PEH geometry and frequency up-conversion mechanisms, especially when combined, are a promising method of overcoming the inherent drawback of such devices due to the random

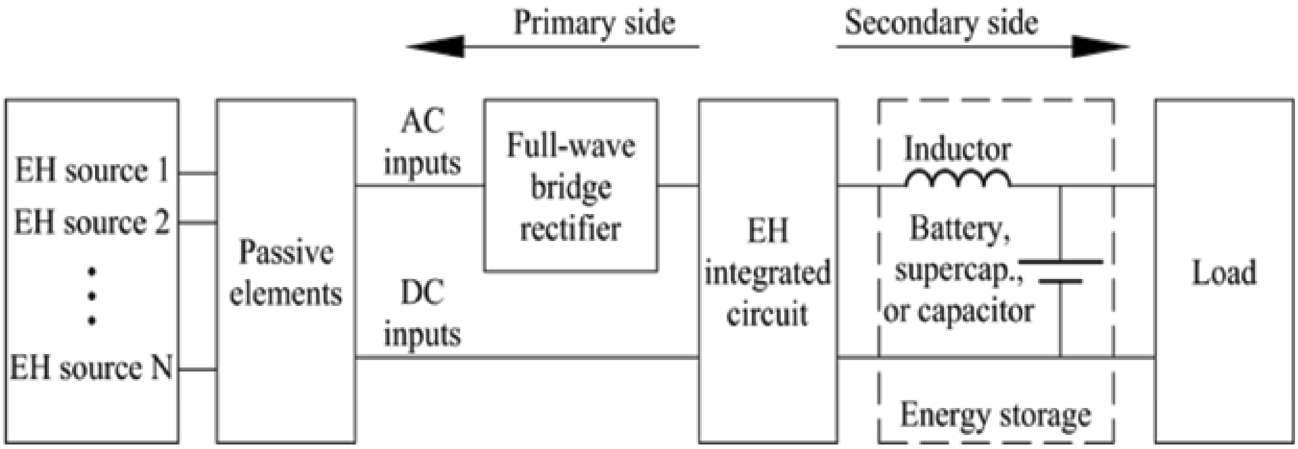


Fig. 14. Wearable EH power management scheme [3]

nature of human motion, particularly evident in wearable applications.

Frequency up-conversion experiments are currently being performed to determine the optimal parameters of the plucking mechanism, i.e., rotational speed as well as the material and number of plectra. Further experimental research is needed to validate the used numerical models, thus perfecting a comprehensive tool for the development of optimized wearable piezoelectric energy harvesting systems.

Thermoelectric energy harvesting technology can then be easily added to a wearable PEH system, making additional electrical energy available, thus forming an innovative hybrid EH system. Such a system can then be used to develop new autonomous wearable devices, suitable to be used in telemedicine, patient monitoring, automated drug delivery and various IoT applications.

Acknowledgements

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