Compact and Low-Frequency Vibration Energy Scavenger using the longitudinal excitation of a piezoelectric bar

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Abstract. This paper introduces an innovative architecture of a piezoelectric harvester, which enables harvesting vibration energy at low frequency using the {33}-transduction mode of a piezoelectric element. Unlike cantilevers integrating ferroelectric material combined with interdigitated electrodes, the concept that we propose is based on the elongation/compression excitation of a piezoelectric bar.

1. Introduction
The conversion of mechanical energy from the environment into useable electrical energy using piezoelectric materials is a well-known technique, which has been widely investigated during the last decade. Most of the time, this vibration energy is located at low frequency (typically from 10-100 Hz) and the corresponding level of acceleration is low. Most of the presented works focus on compliant structures that use flexion mode (cantilevers, clamped-clamped beams, spirals, membranes…) in order to combine low resonance frequency of the structure and actuation of stiff piezoelectric material. The energy is then converted through the \{31\} piezoelectric transduction mode (Figure 1 a). Also, several works have been presented where the energy is rather converted using the \{33\}-transduction mode (Figure 1 b) using interdigitated electrode [1,2]. This transduction mode offers higher coupling coefficients but requires an additional poling step since the polarisation vector must be orientated in the layer plane. Furthermore, only a part of the piezoelectric material is actually actuated. The goal of this paper is to propose a compact, low frequency device using the \{33\}-transduction mode excited by elongation/compression of a piezoelectric bar (Figure 2). Though the excitation of the piezoelectric elements via direct excitation as illustrated in Figure 2 (a) is not suitable for scavenging low frequency vibration energy because of the very high corresponding resonant frequency, it becomes possible with our structure.

The first part of the paper focuses with the description of the mechanical converter able to work at low frequency and providing an amplification of the applied force on the piezoelectric ceramic bar. The second part is dedicated to the electromechanical simulation of the whole device including the piezoelectric transducer. Moreover, for a given electrical power, we can adapt the voltage output by changing the number of layers in the piezoelectric stack.

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2. Design of the mechanical amplifier

The \{33\} transduction is very attractive since it is characterized by three times higher conversion efficiency than the transverse \{31\}-transduction. However, the stiffness of most of the piezoelectric materials makes the \{33\}-mode very unpractical for energy scavenging at low frequencies - where most of the ambient vibration energy is localized. Based on previous works on piezoelectric micro-actuators \[3-5\], we propose a device architecture that converts a large-displacement/low-force excitation into a small-displacement/high-force excitation applied on a piezoelectric element (Figure 2). This structure is therefore termed “force amplifier” or simply “amplifier”. With such a device, the use of the elongation/compression of a piezoelectric bar for vibration energy scavenging at low frequencies becomes possible.

2.1. Description of the mechanical transducer

The proposed amplifier is used in combination with a proof mass, which is distributed on both parts of the device and tightly attached to the input arm with fixation pins (Figure 3 a). When acceleration is applied on the structure, the displacement of a proof mass creates a rotational moment on the input arm. This input moment is then converted into a pure axial force and transferred to the piezoelectric element by a series of two lever stages (Figure 3 b and c). These are created from the combination of rigid parts and flexural hinges which width is set such as to match the desired resonant frequency (Figure 5). The complexity of the amplifier architecture proposed in this study results from a design effort to optimize the generator compactness.

Besides the ability to excite the piezoelectric bar at low frequency, another main advantage of the proposed concept is that it allows the mechanical excitation of the piezoelectric material in the compressive domain only. During the assembly, a pre-stress shim is placed between the piezoelectric bar and the amplifier to achieve the stress bias. This represents a great advantage in terms of device reliability since no tensile force is applied on the ceramics.
2.2. Prototyping
In the frame of this study, we have fabricated a prototype (Figure 4). It is composed of an amplifier made of aluminum alloy, which was fabricated by wire-cut EDM (Electric Discharge Machining), a 3.3 g proof mass mounted on the input arm, and a piezoelectric bar made of PZT NCE51 (from Noliac). The piezoelectric element is 5.7 mm long and its section area is $1.2 \times 1.2 \text{ mm}^2$. The hinges are 50 µm wide. The complete device has a length of 13.5 mm, and the mass diameter is 5 mm. Finite Element Modelling (FEM) simulation returns a device resonance frequency at 25 Hz.

![Figure 3](image1)

**Figure 3.** a) Displacement of the proof mass is transferred to the amplifier through the input arm, b) negative stress is applied on the piezoelectric bar when mass is moved upward, and c) positive stress is applied on the piezoelectric bar when mass is moved downward.

2.3. Mechanical coupling
The simulated load characteristic of the amplifier is illustrated on Figure 6. Under a 40 mN input force (1 mm displacement of the mass), the resulting blocked force is 2.8 N. The gain relative to the force is then calculated as 70. The stroke of the amplifier is about 1 µm. When the amplifier is associated with a piezoelectric element which stiffness is 50 GPa, the corresponding applied force and deformation are 2.3 N and 200 nm respectively. The operation point is clearly not optimal and the mechanical coupling is about 1% only. Further design optimization is still required (hinges, lever lengths…) in order to increase this value.

![Figure 4](image2)

**Figure 4.** a) Naked 10mm long amplifier, b) amplifier mounted with a commercially available multi-layered piezoelectric actuator and pre-stress shim, c) final assembly with proof mass.

![Figure 5](image3)

**Figure 5.** Variation of the resonance frequency of a device made of Aluminium alloy with a piezoelectric element which stiffness was arbitrarily set at 200GPa. These data result from a Finite Element Modelling.

![Figure 6](image4)

**Figure 6.** Load characteristics of the amplifier. The blocked force is 2.8 N and the stroke is 1 µm. With a piezoelectric element which stiffness is 50 GPa, the applied force is 2.3 N and corresponding displacement is 200 nm.
3. Electromechanical modelling

Though the mechanical coupling of the structure is not optimized yet, the above-described piezoelectric scavenger has been fully characterized using FEM software with the aim of assessing the power that could be scavenged.

3.1. Monolithic piezoelectric bar

In this case, we assume a monolithic piezoelectric element mounted together with the amplifier i.e. there are only two electrodes located on both ends of the bar. With an input acceleration of 0.1g, the generated mean power transferred to a 1.1 GΩ optimal resistive load is 9 µW. The corresponding RMS voltage is 99 V (Figure 7). This high value of the output voltage comes from the piezoelectric element design, which induces a high electrical impedance.

![Figure 7](image)

**Figure 7.** Scavenged mean power and corresponding RMS voltage under a 0.1 g harmonic acceleration. The device resonant frequency is about 25 Hz.

3.2. Multi-layered piezoelectric bar

In order to get a voltage that fit the requirements regarding the design of the AC/DC and DC/DC converter, we propose to use low-impedance configuration: a multilayered piezoelectric bar with the elementary piezoelectric elements connected in parallel (Figure 8 a). Because the amount of piezoelectric material and the applied force remain unchanged, this configuration is expected to return the same power as the monolithic configuration. Based on the fact that 3V DC voltage is usually required for powering rechargeable batteries for instance, we adapt the number of piezoelectric layers such as to set the output voltage to 3V. Using, for instance the PZT NCE51, this number of layers is set to 30 (Figure 8).

![Figure 8](image)

**Figure 8.** a) Connection scheme for a multilayered piezoelectric bar and b) simulated variation of the output voltage versus the number of layers. For instance, a 3V output voltage is obtained with 30 piezoelectric layers c) mean output power as a function of number of layers.
4. Conclusion

In this paper, we presented an original piezoelectric energy scavenger architecture that allows combination of elongation/compression excitation of a piezoelectric bar with operation at low frequency. This electromechanical transduction mode is known to be more efficient than the traditional {31} mode, which is commonly implemented in bending structures. Furthermore, it has been presented how this approach allows shifting the stress applied to the piezoelectric element in the compressive domain only using a pre-stress shim. Finally, it was shown that by setting the number of piezoelectric layers, the output voltage can be set independently to the output power.

Acknowledgements

This work was supported by the French OSEO project HBS in the framework of FUI 1009044V.

References

[1] Q.Q. Zhang et al., “Lead zirconate titanate films for d33 mode cantilever actuators”, Sensor and Actuators A 105 (2003) pp. 91-97.
[2] P. Muralt et al., “Vibration energy harvesting with PZT micro device”, Procedia Chemistry, Proceedings of the Eurosensors XXIII conference, vol.1, no.1, (2009), pp.1191-1194.
[3] S. Basrour et al., “Mechanical characterization of microgrippers realized by LIGA technique”, International Conference on Solid-State Sensors and Actuators, Transducers ’97 (1997), pp. 599-602.
[4] F. Claeyssen, R. Le Letty, N. Lhermet, “Actionneur piezoactif amplifié à raideur élevée”, patent FR 95 12598 (1997).
[5] http://www.dynamic-structures.com.