Self-powered resonant frequency tuning for Piezoelectric Vibration Energy Harvesters

B. Ahmed-Seddik, G. Despesse, S. Boisseau, E. Defay

CEA-LETI, Minatec Campus, Grenoble, France

Ghislain.despesse@cea.fr

Abstract. This paper reports on the design, fabrication and testing of an innovative 33-mode piezoelectric vibration energy harvester (VEH). This system is able to change its resonant frequency in real time to follow the main frequency of a vibration source. The system proposed in this paper enables to adapt VEH characteristics (resonant frequency, electrical damping) to vibration parameters variations (frequency and amplitude) in order to optimize the extraction of energy and then the output power at any time. This solution allows up to 40% of resonant frequency tuning ratio; moreover, the adaptation is made in real time and the consumption of the regulation electronic is less than 10% of the VEH output power (480µW@0.1g-276Hz).

1. Introduction

During the last decades, a large attention has been given to micro-energy harvesters. This is mainly due to the increasing number of implemented low power sensors in different fields such as health, buildings, transportation…. These sensors are in most cases powered by batteries. The main drawback of batteries is the need for a continuous control of their state of charge, their recharge and their replacement that may become tedious and expensive. Thus, in order to overcome these limitations, one of the most promising solutions is to harvest the surrounding energy. In our environment, we can find many types of harvestable energy, for example: mechanical energy, thermal energy and radiant energy (solar, infrared, radiofrequency). This paper is dedicated to the harvesting of mechanical vibrations produced by cars, trains, variable speed engines and so on.
Theoretical models show two important points to improve VEH efficiencies [1]: *(i)* equality between vibration frequency and resonant frequency, and *(ii)* equality between mechanical damping and electrical damping.

For the first point, many works have been carried out (most of them are summarized in [2]):

- Increasing the bandwidth by increasing the mechanical damping. This solution induces an output power always lower than a less damped system.
- Increasing the bandwidth by increasing the electrical damping (part of mechanical energy stored in the mechanical spring turned into useful electrical energy) [3]. This solution induces a higher output power outside of the resonant frequency and less power on the resonant frequency unless adjusting in real time the electrical damping (the optimal electrical load from a highly coupled system).
- Increasing the bandwidth by adding a non-linear effect [4-5]. This solution induces in many cases a relative displacement saturation effect, reducing the maximum power peak.

Yet, it does not really increase the output power outside of the resonant frequency unless in some specific cases [6].

- Increasing the bandwidth by dynamically adjusting the resonant frequency to the input frequency [7-10]. This solution enables to get the maximum output power even if the input vibration frequency changes over time. Nevertheless it requires a feedback loop that consumes one part of the output power and is not appropriate for random vibrations.

From measurements we made in different environments, it appears that the vibration source has its energy concentrated on one frequency that may change over time. The main vibration frequency can change for example if the system has a mobile part moving at variable speeds (i.e. car engines, variable speed processing machines…). Finally, at a given time, the energy is mainly present at only one frequency; it is then interested to make the harvester able to resonate on that frequency to get the maximum output power. A suitable solution is a system able to adapt its resonant frequency in real time, without compromising neither the operating frequency bandwidth nor the power density. The aim of the work presented in this paper is to show that it is possible to make a system able to follow in real time the main vibration frequency of the vibration source on a quite large frequency band (up to 40% of frequency variation), with a power consumption that does not exceed 10% of the harvested power.

For the second point, that is to say, adapting in real time the electrical damping forces in order to maintain an optimum point of electrical energy extraction, only one study has been carried out [11].

The system we propose in this paper is based on an active method for tuning the resonant frequency and the electrical damping at the same time in order to keep, in real time, the best working conditions for the VEH, maximizing its efficiency and its output power.

2. Resonant frequency change mechanism

Piezoelectric materials are characterized by an elastic compliance *s* which is dependent on the applied electrical conditions. The piezoelectric bulk stiffness is lower when the material is placed in short circuit (s^E) than in open circuit (s^D). s^D and s^E are linked by equation (1) where *d* is the piezoelectric coefficient, ε the dielectric permittivity and *k* the electromechanical coupling coefficient.

$$s^D = s^E - d^2 / \varepsilon^T \Leftrightarrow s^E = \frac{s^D}{1-k^2} \tag{1}$$

Then, the piezoelectric material's stiffness can be adjusted between $1/s^E$ and $1/s^D$ by connecting it to an adjustable electrical load.

Actually, the choice of the electrical load type is primordial: as choosing a dissipative electrical load (e.g. resistor) could damp the mechanical system and dissipate its energy. It is then appropriate to connect a non dissipative load, for example an inductor or a capacitor. In order to easily reach an impedance value close to the piezoelectric one (the optimal load effect is around the piezoelectric impedance), we have chosen to connect a variable capacitor C_s named *shunt capacitance* in parallel with the piezoelectric material. This capacitor is adjustable in order to reach the required resonant frequency between the short circuit and open circuit resonant frequencies. It can be modeled as an increase of the effective dielectric permittivity of the piezoelectric material and then it modifies the piezoelectric material stiffness as shown by the following equation (2).

$$\left.\begin{array}{l} s^D = s^T - d^2/\varepsilon^T \\ C = C_p + C_s \\ C_p = \varepsilon^T \dfrac{A}{t_p} \end{array}\right\} \Rightarrow s^D = s^E - \frac{d^2 A}{t_p\left(C_p + C_s\right)} \Rightarrow E_p = \left(s^E - \frac{d^2 A}{t_p\left(C_p + C_s\right)}\right)^{-1} \tag{2}$$

Parameter	Definition
C_p	*The piezoelectric capacitance of a piezoelectric layer*
C_s	*The shunt capacitance*
t_p	*The piezoelectric thickness*
A	*The piezoelectric electrode surface*
E_p	*Piezoelectric Young's modulus*

To maximize the rate of the resonant frequency change, the most part of the mechanical energy has to be stored in the piezoelectric material. To achieve this purpose, a new design has been proposed and has already been presented in [9, 10].

3. Electrical damping change mechanism

As mentioned above, in addition to track the resonant frequency, the electronic circuit must adapt the electrical damping to the mechanical damping. For this purpose, we propose to adjust the VEH output current by using a second reconfigurable capacitor (C_2) in series with the load (Figure 1). Hence, we suppose that the VEH open circuit voltage is significantly higher than the output voltage on the storage element (e.g. V_{bat}@3V). Finally, the electrical damping can be adjusted in real time in order to maintain the electrical damping equal to the mechanical damping and then to maximize the VEH efficiency.

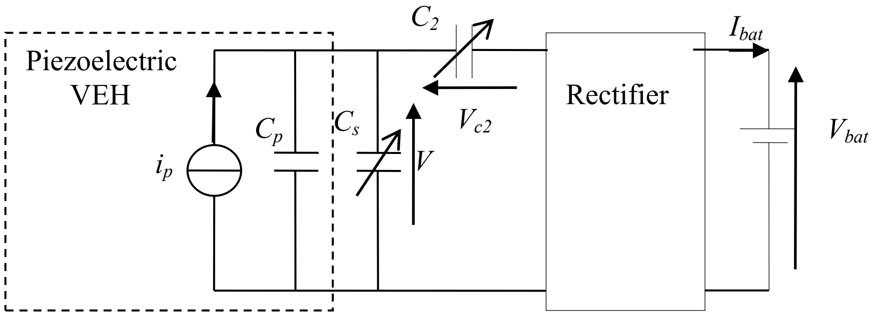


Figure 1. Combined electrical damping / resonant frequency adjustment mechanism

C_2 has also an effect on the resonant frequency, like C_s. Yet, its effect is automatically compensated by the feedback loop on C_s.

4. Feedback loop mechanism

C_s and C_2 are composed of a reconfigurable C, $2C$, $4C$.. $2^N C$ network and are adjusted by two feedback loops working as a Maximum Power Point Tracker (MPPT) with a significantly different feedback time constants (Figure 2).

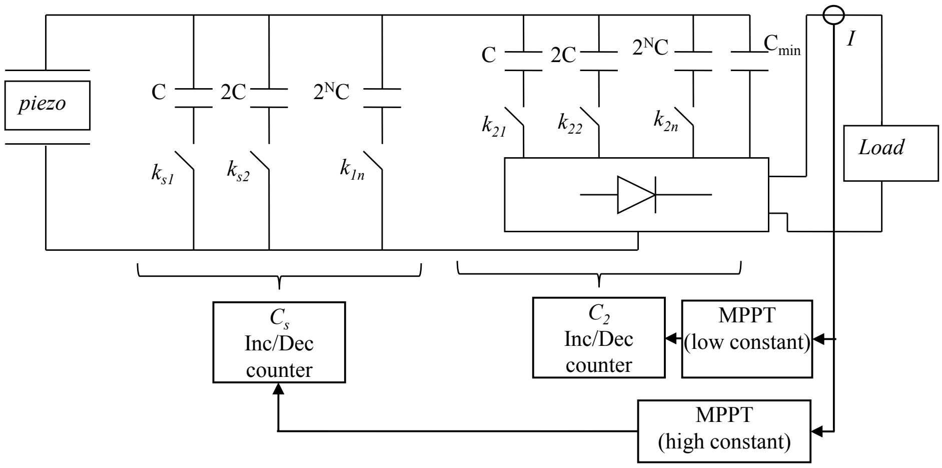


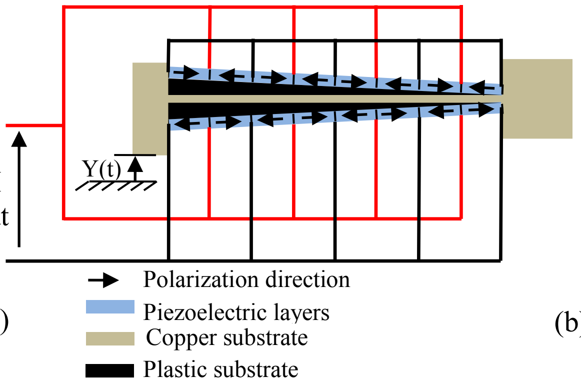
Figure 2. Feedback loops mechanism

The Feedback loops controllers are digital with a clock generated by the vibration itself and with a digital input of '0' if the output power decrease and '1' if it increase. The feedback loop for C_2 is actuated each 8 vibrations periods while the feedback loop for C_s is actuated each 64 periods. The operation principle is as follow: if the last capacitance change induces an increase of the output power, then the capacitance is changed in the same direction; otherwise the capacitance is changed in the opposite direction. C_s and C_2 are directly controlled by the output bits of 4 bits digitals counters.

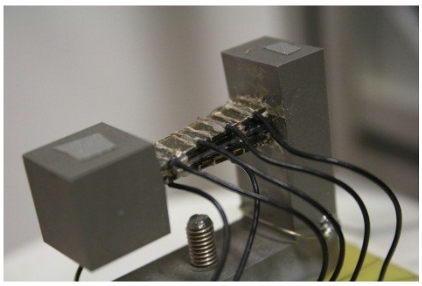
The current flowing through the storage is first converted into a voltage signal by using a current to voltage converter (CVC). The resulted voltage is then filtered in order to remove all the variations related to the periodic oscillation of the VEH and to keep only the variations due to the resonant frequency and the electrical damping changes.

5. Experimental setup

As already mentioned in section 2, in order to maximize the interaction between the electrical conditions and the mechanical behavior, a triangular shape structure has been chosen to homogenize and maximize the energy stored in the piezoelectric material compared to the substrate material. Moreover, to further increase the electromechanical coupling of the device the longitudinal piezoelectric mode (33-mode) has been exploited (Figure 3a). The prototype is presented in figure 4b.



(a)



(b)

Figure 3. VEH with a triangular shape structure (a) principle and (b) prototype

6. Experimental results

Figure 4 shows the harvested power between 200Hz and 300Hz in closed and open loops. The difference between the harvested power and the net output power is the power consumed by the control circuit to adapt in real time the resonant frequency to the vibration source frequency and to provide at the same time the output power on a 3V-storage with an optimized current load. In closed loop, the output power is nearly always higher than in open loop, even by taking into account the full electronic circuits consumption (50µW); moreover, the frequency bandwidth is multiplied by 3 and, outside this frequency range, the output power is clearly higher in closed loop (Figure 4). These results prove that it is possible to electrically adjust in real time the resonant frequency of a piezoelectric harvester system with less than 10% of the harvested power (480µW@0.1g-276Hz). The resonant frequency adjustment is performed every 64 mechanical periods (i.e. around every 350 ms; every 22s was reached by [8] in 2011).

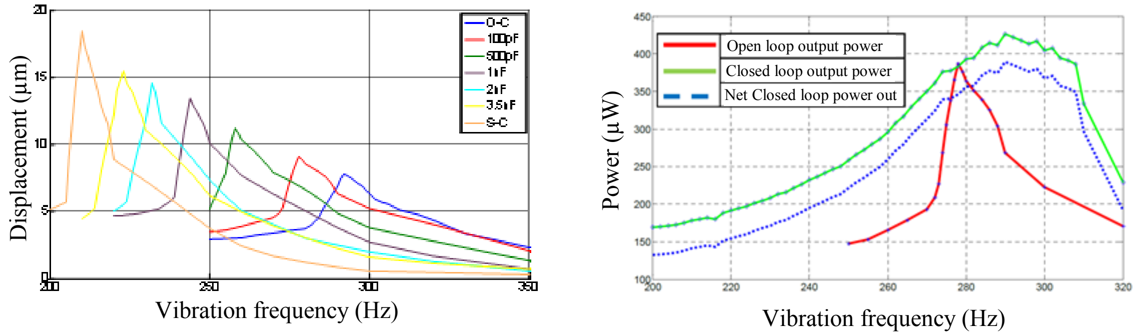


Figure 4. (a) Frequency response as a function of the electrical conditions @ 0.1g and (b) Output power as a function of the input vibration frequency in open and closed loops, with and without the power management consumption

7. Conclusions

The approach presented in this paper allows to efficiently scavenge a vibration which has a main frequency changing over time, and is particularly suitable for transportation systems which work at different speeds. The resonant frequency adjustment is carried out by switching 'on' or 'off' some transistors every few periods of the mechanical vibration. The implementation of this strategy shows that it is feasible to make a complete automatic feedback loop circuit that consumes less than 10% of the VEH output power and able to operate over up to 40% of frequency change and maintaining at the same time the electrical load optimal. The system produces more than 150µW of net power from 220Hz to 320Hz @ 0.1g.

References

[1] Williams C B *et al.* 1996 *Sens. Actuators A: Phys*, **52** 8
[2] Zhu D *et al.* 2010 Strategies for increasing the operating frequency range of vibration energy harvesters: a review *Meas. Sci. Technol.* **21**
[3] Despesse G *et al.* 2008 Mechanical vibrations energy harvesting and power management *Proc. IEEE Sensors* 29.
[4] Blystad L *et al.* 2010 *IEEE Trans on Ultrasonic, Ferroelectric and Frequency Control* **57** 908
[5] Shahruz S 2006 *J. Sound. Vib.* **292** 987
[6] Boisseau S *et al.* 2013 Nonlinear H-Shaped Springs to Improve Efficiency of Vibration Energy Harvesters *J. Appl. Mech* **80** (6) 061013
[7] Morgan B and Ghodssi R 2008 *J. Micrelectromech. Syst.* **17** (1), 85-92
[8] Eichhorn C *et al.* 2011 A smart and self-sufficient frequency tunable vibration energy harvester, *J. Micromech. Microeng*, **21**
[9] Ahmed Seddik B *et al.* 2011 Increased bandwidth of mechanical energy harvester, *Journal of Sensors & Transducers* **13**, Special Issue 62-72
[10] Ahmed Seddik B *et al.* 2012 Wideband mechanical energy harvester based on piezoelectric longitudinal mode *New Circuits and Systems Conference (NEWCAS), IEEE 10th International* **17-20** 453-456
[11] Mitcheson P D *et al.* 2011 *Circuits and Systems II: Express Briefs, IEEE Transactions on* **58**, no 12 792-796