Piezoelectric vibration harvesting device with resonance frequency automatic tracking capability

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ABSTRACT

Further development in the area of vibration energy harvesting is limited by the lack of efficient methods to adapt the harvester to its surroundings. To this end, we propose an innovative passive way of automatic passive resonance frequency tracking.

We present a new approach employing mechanical non-linear behaviour of the system to track the vibration frequency peak. An analytical model representing these nonlinear harvesting systems has been developed and analysed. Experimental results obtained with custom fabricated MEMS devices show an experimentally verified frequency adaptability of over 36% for a clamped-clamped beam device at 2g (1g=9.81m.s^{-2}) input acceleration. We believe that the proposed solution is perfectly suited for autonomous industrial machinery surveillance systems, where vibrations with high accelerations that are necessary for enabling this solution are abundant.

INTRODUCTION

Nowadays, there is a huge interest for wireless sensor networks in industrial or natural environments. However, a challenge is still present to see these networks commonly used: replacing batteries with limited energy capacity that are used as energy sources for the nodes which imply costly periodic maintenance. Piezoelectric ambient energy scavengers are a promising solution to this problem [1]. However, as these scavengers are resonant, their resonance frequency has to match the dominant frequency in the surroundings to be efficient. Unfortunately, precision of fabrication and scattering of material properties lead to variations in resonance frequency of the devices. As a consequence, an energy harvesting device with adaptable resonance frequency is needed to make this energy scavenging method more efficient [2].

Two kinds of solutions can be found to tune resonance frequency of vibration energy harvesters:

-active methods need an external action that modifies the device mechanically ([3], [4]) or electrically ([2]) in response to changing excitation frequency. Usually, an active frequency tuning method is more efficient than passive methods, but requires a large amount of energy to tune the system. This amount of energy is too important compared to the possible energy harvested, so this system is not suitable for energy harvesters.

-passive methods consist of harvesters with bandwidth large enough to accept frequency changes ([5], [6]). They are actually the only tuning devices usable for energy harvesting.

In this work, an innovative passive way of resonance frequency automatic tracking is presented. Nonlinear energy harvesting has already been proposed by Cottone and al [7] with a system based on a bistable oscillator to increase the gain of power harvesting, but not to adapt the system to the surroundings. We propose a new approach using mechanical non-linear behaviour of the system, so that the nonlinear system tracks the vibration frequency peak.

THEORY

The harvesters studied are clamped-free (C-F in the following, Figure 1.a) or clamped-clamped (C-C in the following, Figure 1.b) silicon beams with seismic mass, with a piezoelectric thin layer deposited on top. Our structures are resonant, with a seismic mass implemented to reduce the resonance frequency. The piezoelectric layer transforms mechanical energy into electrical energy.

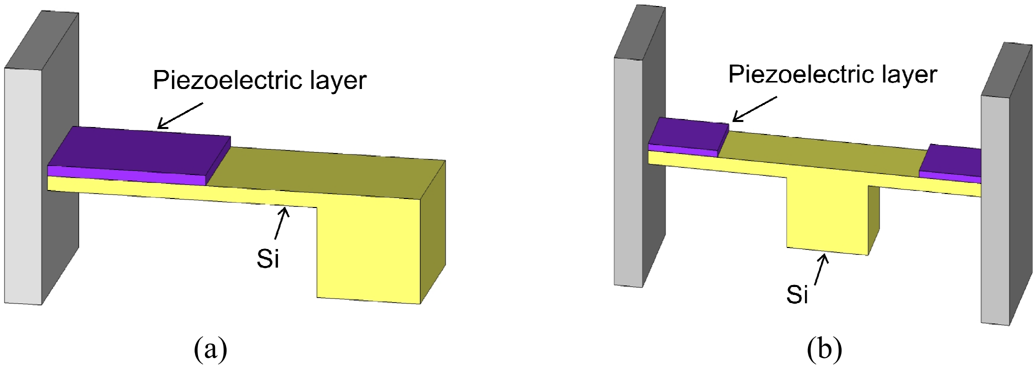


Figure 1: Microgenerator's structures and materials. (a) Clamped-free beam with seismic mass. (b) Clamped-clamped beam with seismic mass.

The simplest way to model this kind of harvester is a mass spring system [8], as represented in Figure 2. In this model, the viscous damper *d* represents the lost of the energy harvested, which is supposed not to influence the vibration source. The displacement *z(t)* of the seismic mass is related to the frame displacement *y(t)* by equation 1.

$$m\ddot{z}(t) + d\dot{z}(t) + kz(t) = -m\ddot{y}(t) \qquad (1)$$

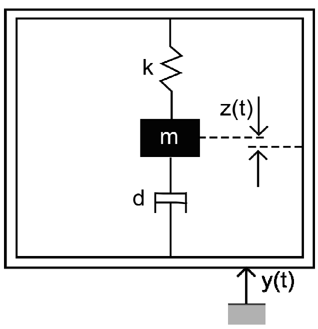
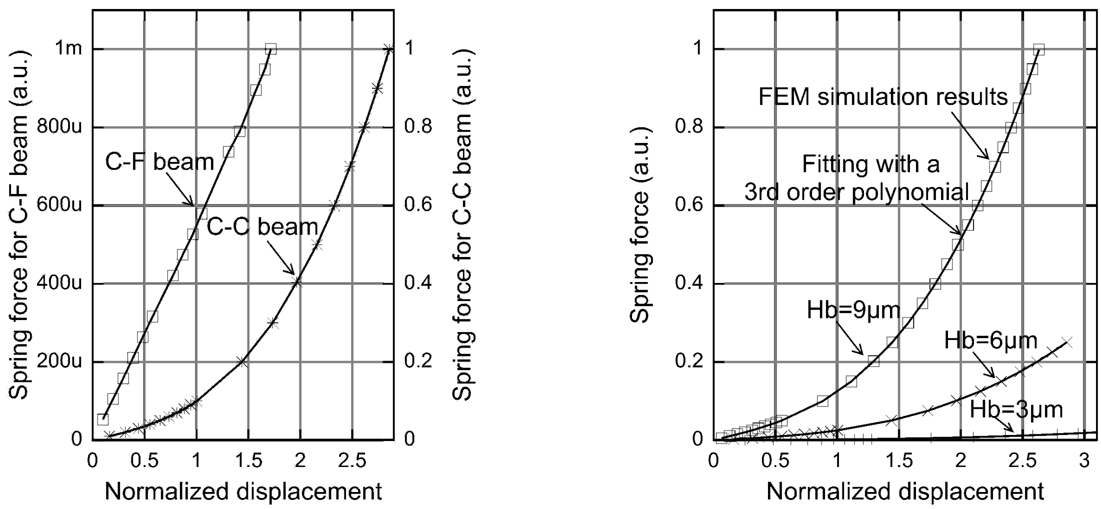


Figure 2: Schematic representation of a resonant microgenerator with a seismic mass *m*, a spring stiffness *k* and a damper d [8].

The nonlinearities of the system can be introduced by making the spring nonlinear with respect to deformation.

There are two kinds of nonlinearities in piezoelectric vibration energy harvesters: mechanical nonlinearity and material nonlinearity. Mechanical nonlinearities are related to large deflection effects, when the beam is subject to large displacements. Material nonlinearities are related to a nonlinear strain-stress relationship [9]. As silicon used in this study is in monocrystaline form, material nonlinearities mostly come from the piezoelectric layer, which was PZT (Lead zirconate titanate) or AlN (Aluminium Nitride). Mechanical nonlinearities tend to hardening effects, and material nonlinearities in piezoelectric layer tend to softening effects [10]. For a C-C beam, because of the clamps at both ends, the beam necessarily stretches as it deflects in its transverse motion. It is not the case for a C-F beam. As a consequence, mechanical nonlinearities are much more important for C-C beams than for C-F beams: for the same mass displacement, the C-C beam works in a nonlinear domain as the C-F does not (Figure 3.a). Therefore, C-C beams will be chosen for nonlinear energy harvesting.



(a) (b)

Figure 3: (a) Normalized spring force versus displacement normalized by the thickness of the beam for C-F beam and C-C beam. (b) Normalized spring force versus displacement normalized by the thickness of the beam, for a C-C beam with seismic mass, for 3 different thicknesses of the beam H_b.

Mechanical nonlinearity becomes predominant for C-C beam when the displacement gets close to the width of the beam as we can see on Figure 3.b, obtained with static FEM simulations with ANSYS^{TM}. The spring force function versus normalized displacement fits to a polynomial function F_k (equation 2) with less than 1% error. According to this, we will consider that the spring force varies with the mass displacement by the following equation 2. Doing this, we will only consider the mechanical nonlinearities. This hypothesis is perfectly suited for C-C beams, for which mechanical nonlinearities predominate.

$$F_k = k_0 z(t) + k_1 z^3(t) \tag{2}$$

As a consequence, the stiffness k varies with the square of the displacement:

$$k = k_0 + 3k_1 z^2(t) \tag{3}$$

Reporting these results in equation 1, and assuming sinusoidal excitation, the system can be characterized by a nonlinear differential equation (4) of the mass displacement *z(t)*, with $w_0 = \sqrt{k_0/m}$, $\lambda = d/2m$, $\beta = k_1/m$, and A_{in} the amplitude of input vibration acceleration.

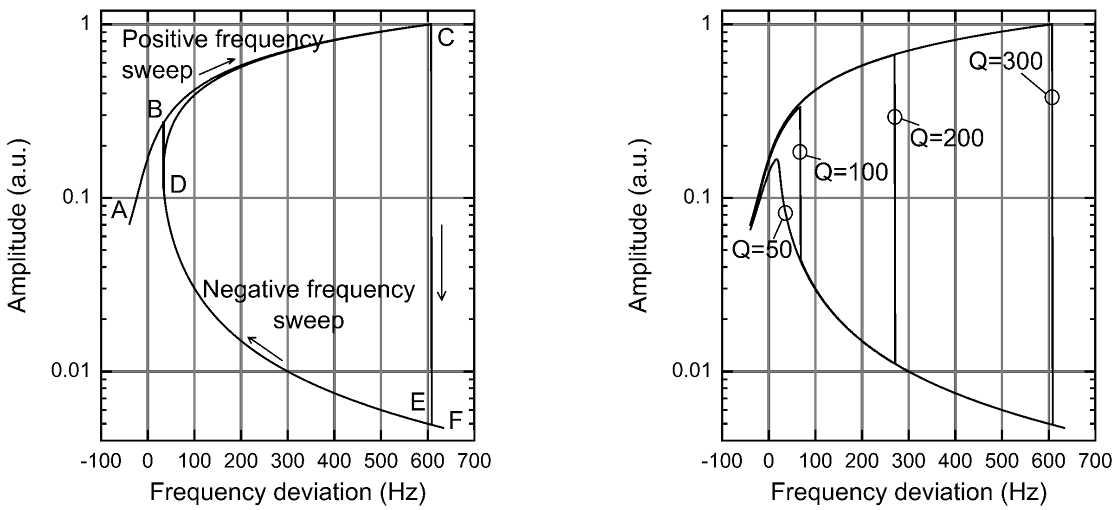
$$\ddot{z}(t) + 2\lambda\dot{z}(t) + w_0{}^2 z(t) + \beta z^3(t) = -A_{in}\cos(wt) \tag{4}$$

This equation is characteristic of a forced Duffing oscillator [11], and will be used for numerical simulations of the system, to understand its behaviour and determine the influential parameters.

RESULTS

Simulation results

These nonlinearities lead to a bending of the frequency response, and a resonance frequency shift. For highly nonlinear devices such as C-C beam, a hysteresis appears in the frequency response for high accelerations, depending on the direction of frequency excitation sweep, as in Figure 4.a. When the frequency sweep direction is positive, the displacement amplitude follows the curve ABC, before to jump from C to E, to then follow the branch EF. On the other hand, when the frequency sweep direction is negative, the oscillation amplitude follows the curve FEDBA, with a jump between D and B. As a consequence, if we are harvesting energy at a working point in the BC zone, if the vibration frequency increases, our system will follow the frequency variation.



(a) (b)

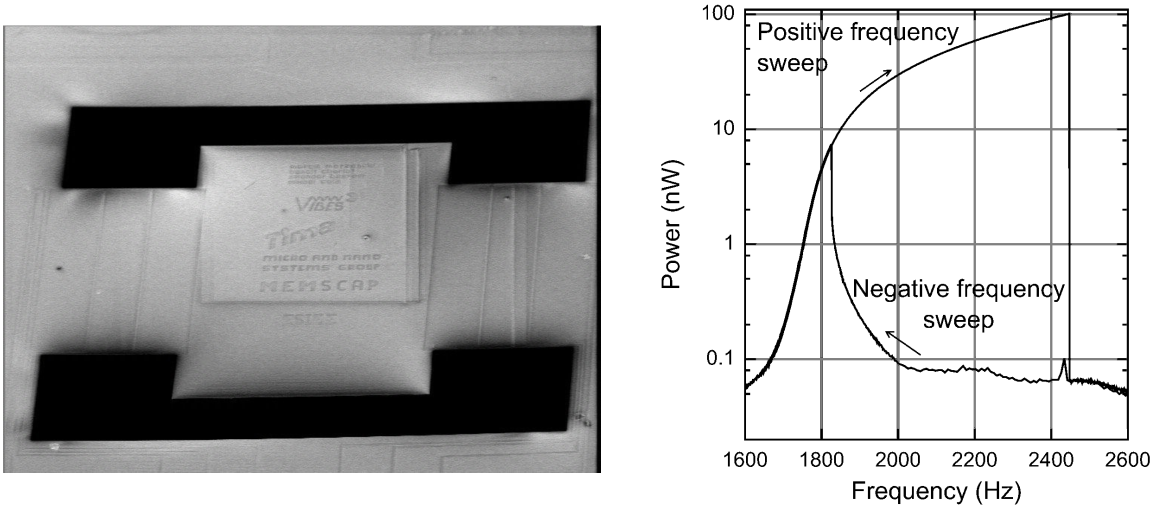
Figure 4 : (a) Nonlinear system response numerically simulated (normalized displacement amplitude versus frequency deviation) obtained for a linear resonance frequency of 1800Hz, a

quality factor of 300, a nonlinear stiffness β=6.10^{20}m^{-2}s^{-2}, and an input acceleration of 2g, (b) Normalized frequency response of the system for different quality factors.

Material properties play a strong role in the device behaviour. As we can see in Figure 4.b, the larger quality factor we have the larger bandwidth we will get for a fixed acceleration, which is exactly the contrary for a linear system. As a consequence, high quality factor's materials are needed to use this non linear tracking method, and crystal or quasi-crystal are the more suited materials for these applications.

<u>Experimental results</u>

This nonlinear harvesting method has been tested experimentally using a custom made MEMS clamped-clamped beam with an AlN piezoelectric layer. As in simulation, a nonlinear forced oscillator behavior has been observed, and leads to 36% of resonance frequency adaptability for an input acceleration of 2g. Thus, the power harvested is low, and the efficiency has to be improved by optimizing the design of the harvester.



(a) (b)

Figure 5: (a) C-C beam device (b) Experimental results for clamped-clamped beam with seismic mass with a PZT piezoelectric layer connected on optimal power transfer resistance.

This nonlinear energy harvesting method is perfectly suited for industrial applications, as for example rotating machines, where high g accelerations are present, and for which the vibration frequency changes as the machine speed varies.

PERSPECTIVES

Further works will concentrate on design of new structures, and on developing a new physical model for clamped-free beams and clamped-clamped beams, considering mechanical nonlinearities and piezoelectric material nonlinearities. This model will allow us to optimize structures for nonlinear energy harvesting.

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REFERENCES

[1] M. Marzencki, Y. Ammar, and S. Basrour, Integrated power harvesting system including a mems generator and a power management circuit. *Sensors and Actuators A: Physical*, vol. 145-146, pp. 363–370, 2008.

[2] S. Roundy, E. S. Leland, J. Baker, E. Carleton, E. Reilly, E. Lai, B. Otis, J. M. Rabaey, V. Sundararajan, and P. K. Wright, Improving power output for vibration-based energy scavengers. *IEEE Pervasive Computing*, vol. 4, no. 1, pp. 28–36, 2005.

[3] V. R. Challa, M. G. Prasad, and F. T. Fisher, High efficiency energy harvesting device with magnetic coupling for resonance frequency tuning. In *Proc. of the SPIE,* Volume 6932, pp. 69323Q-69323Q-12, 2008.

[4] Gianluca Piazza, Reza Abdolvand, Gavin K. Ho, and Farrokh Ayazi, Voltage-tunable piezoelectrically-transduced single-crystal silicon micromechanical resonators. *Sensors and Actuators A: Physical*, vol. 111, no. 1, pp. 71–78, Mar. 2004.

[5] S. Shahruz, Design of mechanical band-pass filters for energy scavenging. *Journal of Sound and Vibration*, vol. 292, no. 3-5, pp. 987–998, May 2006.

[6] G. Despesse, J. J. Chaillout, T. Jager, J. M. Léger, A. Vassilev, S. Basrour, and B. Charlot, High damping electrostatic system for vibration energy scavenging. In *Proc. of SoC-EUSAI '05,* Grenoble, France, pp. 283–286, 2005.

[7] F. Cottone , H. Vocca, and L. Gammaitoni, Nonlinear energy harvesting. *Physical Review Letters*, vol. 102, no. 8, p. 080601, 2009.

[8] C. B. Williams and R. B. Yates, Analysis of a micro-electric generator for microsystems. *Sensors and Actuators A: Physical*, Sensors *and Actuators A: Physical*, vol. 52, no. 1-3, pp. 8–11, 1996.

[9] G. Sebald, L. Lebrun, and D. Guyomar, Modeling of elastic nonlinearities in ferroelectric materials including nonlinear losses: application to nonlinear resonance mode of relaxors single crystals. *IEEE Trans.Ultrason. Ferroelectr., Freq. Control*, vol. 52, no. 4, pp. 596–603, 2005.

[10] S. Mahmoodi, N. Jalili and M. Daqaq, Modeling nonlinear dynamics, and identification of a piezoelectrically actuated microcantilever sensor. *Mechatronics, IEEE/ASME Transactions on*, vol. 13, no. 1, pp. 58–65, Feb. 2008.

[11] L. Landau and E. Lifshitz, *Mechanics*. Pergamon Press, 1976, no. ISBN 0-08-021020-1.