3D VIBRATION HARVESTING USING FREE MOVING BALL IN PZT MICROBOX

Eric Simon[*], Yuichiro Hamate, Sumito Nagasawa, Hiroki Kuwano
Nanomechanics Department, Tohoku University, Sendai, Japan
*Presenting Author: eric.simon@nanosys.mech.tohoku.ac.jp

Abstract:
A novel approach to PZT energy harvesting is proposed. Through an experimentally confirmed simulation, the new design was shown to offer a much wider range of resonant frequencies, namely below 100Hz, and a much more isotropic behavior than cantilever structures; although when exposed to 5μm vibration at 100Hz, the power density was evaluated to 50nW.cm^{-3} for a 2.1mm unit, and to 18nW.cm^{-3} when scaled down to 0.01mm. The resonant behavior of the system was also identified and linked to the relative backlash of the rigid ball encapsulated in the structure comparatively to the excitation amplitude. Finally, design optimization is discussed.

Keywords: vibration energy harvesting, ball moving, wide band resonance, collision

1. INTRODUCTION

In the last few decades, much progress has been observed in microtechnologies. Hard drives and printers are the most obvious benefactors, but the development of MEMS is also constantly contributing to many other aspects of one's life. Nowadays, much research is aiming at the development of independent microsystems capable of communicating and forming networks. The main concept is that of a wireless sensor network: microsensors would be scattered in an environment, and those would measure some specific data such as temperature, vibration, etc; the data of each sensor would then be gathered through a wireless network and processed to obtain real-time large scale data about the environment.

Unfortunately, the development of microsystems has been faced with one major problem: the energy supply. At the macroscopic scale, independent systems usually get their energy from batteries. However, at the microscopic scale, batteries are impractical, as recharging becomes problematic, and their scattering poses an environmental threat.

Among alternative power generators, energy harvesters have attracted much attention. An environment constantly undergoes many physical fluctuations, such as temperature variation, vibrations and air displacement. These fluctuations can be converted in electrical energy through the use of microtransducers, in order to power microsystems. Since environmental vibrations offer the second highest energy density, after solar power [1]; and since piezoelectricity is one of the most efficient way of converting mechanical energy [1]; piezoelectric harvesters of vibration have become some of the most common subjects of research. The basic design usually involves a cantilever covered at least on one side with a layer of a piezoelectric material. Under vibration, the cantilever bends and the piezoelectric layer is deformed so as to produce a periodic electric field. However, typical vibrations in Nature have frequencies below 100Hz [1], and do not show preferential orientation. Also a cantilever is difficult to achieve its resonant frequency below 100 Hz.

In this paper, a novel approach to PZT energy harvesting using free moving ball in piezoelectric material box is proposed. Design, simulation, and fundamental experimental results of the novel method are shown.

2. VIBRATION HARVESTING USING A FREE MOVING BALL IN A PIEZOELECTRIC MATERIAL BOX

The concept consists in enclosing a solid ball in a PZT box, as shown in Fig. 1. When shaken, the ball repetitively collides with the walls and the consequent deformation is converted in an electrical impulse due to the piezoelectric attribute of the material. The performance of such design is therefore almost independent of the vibration orientation, and could prove to be much more responsive to frequencies below 100Hz.

In this paper, the concept is first tested at the large scale by numerical simulation and compared with experimental equivalent. Following the validation of the simulation of the large scale model, smaller versions, down to a tenth of the experimental model, are simulated. Finally, some conclusions on the validity of the concept are drawn from the experimental and simulated results, and some design considerations are brought up.
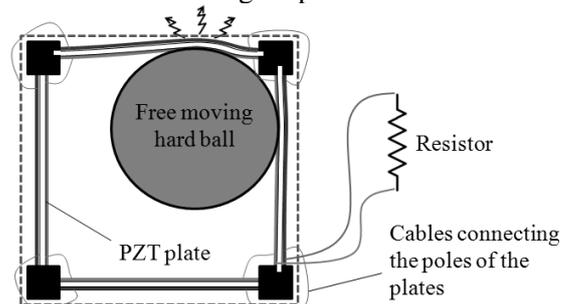

Fig. 1: Scheme of the vibration harvesting concept

3. VALIDATION OF THE SIMULATION

3.1 Single collision simulation test

In order to evaluate the power potential of the concept, a simulation was intended. However, the simulation, done on ANSYS, is complex, involving simultaneously piezoelectricity as well as contact elements. It is therefore necessary to validate the model by comparing the results with that of an equivalent experiment. The first experiment consisted in letting go of a steel ball of 2mm of diameter at a given height, so it would have a predefined speed when colliding against a PZT plate of dimension 9x5.5x0.45mm^3. The PZT plate is connected to a resistor (100Ohm) and an oscillator measures the voltage output (fig. 2.a). The simulation involved a 9x5.5x0.45mm^3 plate with the mechanical and piezoelectric properties of PZT, fixed along two edges, and a steel ball thrown at given speeds against it. Since the vibration frequency of the ball is far higher than that of the plate, the object was configured as rigid.
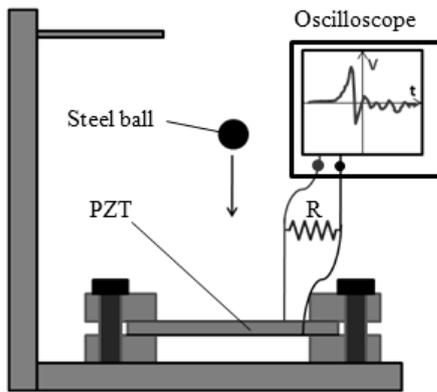The results showed good agreement between the simulation and the experiment (fig. 2.b).

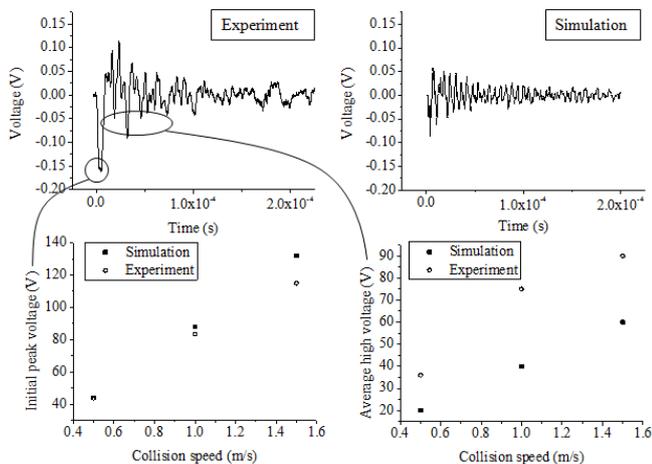Fig. 2.a: Experimental setup for the comparison of experimental and simulated collision.

Fig. 2.b: Top: experimental and simulated output of the collision in similar conditions. Bottom: comparison of the penetration and average voltages in simulated and measured cases, for various collision speeds.

On a collision speed scale ranging from 0.5m.s^{-1} to 1.5m.s^{-1}, the output voltage was of the same order of amplitude, with an error below 17% in terms of initial peak voltage and average high voltage; the oscillation frequency of the simulation was 8% higher than that of the experiment. A low frequency perturbation was also observed in the experiment (fig. 2.b), likely caused by the imperfect base supporting the PZT plate. The simulation of the signal generated by the collision has been judged accurate enough to warrant its use in the next step of the validation. Further experimentation showed that the initial impact voltage and the rebound speed are proportional to the collision speed, and that the collision energy is proportional to the mass of the ball. Therefore, it was concluded that the electrical energy generated following a collision is proportional to the kinetic energy of the ball.

$$E_{generated} = \alpha . \frac{1}{2} m v^2 \qquad (2)$$

Where m is the mass of the ball, v is its speed, and α is the energy conversion factor, function of the properties and dimensions of the PZT plate.

3.2 Multiple collisions simulation test

The next step of the study was the comparison of the energy generated by a large model of the PZT box in a two dimensional context. Therefore, an open box was fabricated and PZT plates (6x13x0.45mm) were installed on each of the four walls, with a spacing of 6.5mm between opposite walls. A steel ball of 6mm diameter was inserted in the middle. The 0.5mm of freedom inside the box allowed the ball to move freely in the horizontal plane when submitted to vibration along the plane (fig 3). The PZT walls would be connected to resistors and the voltage measured.
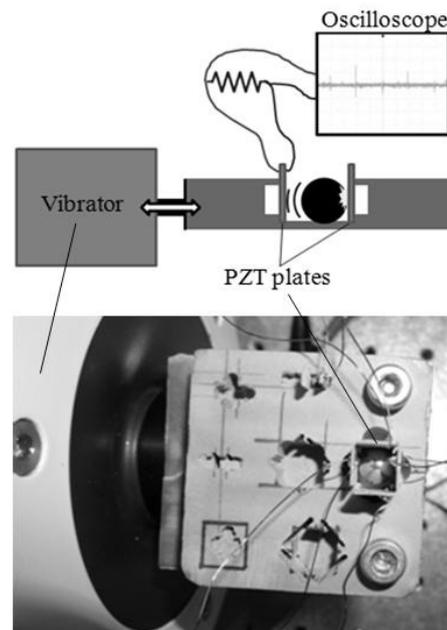

Fig. 3: Top: Schema of the experimental setup.
Bottom: Photography of the experimental setup.

In order to simulate this setup, two steps were necessary: first, the energy conversion ratio and the rebound speed were calculated by simulating a single collision with the appropriate dimensions in ANSYS; then using Matlab, a program was written to calculate the trajectory and the successive collisions of a circle inside a vibrating square, based on those two parameters. In order to simplify the program, air resistance and ball rotation were neglected.

Results were compared for vibration amplitudes ranging from 50μm to 150μm, and frequencies ranging from 50Hz to 150Hz. Similar collision frequencies and voltage peaks have been observed in all cases (fig. 4).

It was also noted that when the amplitude was sufficiently high, the collision frequency would become twice that of the vibration. Following the comparison, the combined simulation with ANSYS and Matlab was judged accurate enough to warrant its use to calculate the energy output at a tenth of the size.
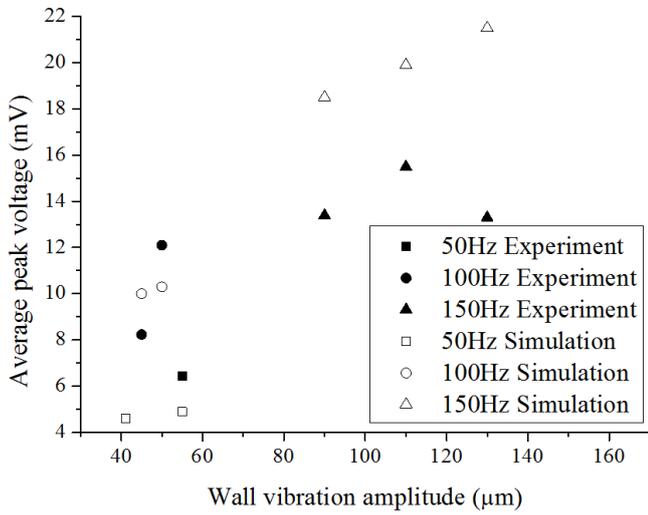

Fig. 4: Comparison of average collision voltage depending on the vibration amplitude, in simulated and experimental models.
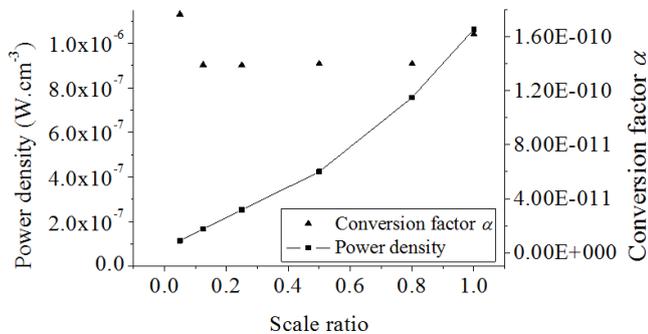

Fig. 5: Simulated evolution of the power density and the conversion factor with the scaling down of a 2.1mm box covered with 2x2x0.2mm^3 PZT plates connected to 1500Ohm resistors, encapsulating a 2mm steel ball.

3.3 Practical application of the simulation

The final step of the study consisted in applying the combined simulation in order to evaluate the power generated, but also to better understand the impact of the parameters on it. An initial model was defined: A 2mm steel ball confined in a box of side length 2.1mm and which walls are covered with 2x2x0.2mm PZT plates and connected to 1500Ohm resistors. The energy generated was then calculated for both the 1:1 and the 1:20 scaled down versions of the model. Further simulations were also done with 100Ohm resistors.

4. RESULTS AND DISCUSSION

4.1 Analysis of the results

The 2.1x2.1x2.1mm^3 PZT box vibrating at 100Hz with an amplitude of 5μm was calculated to generate 50nW per cm^3, while the 0.1x0.1x0.1cm^3 equivalent box would produce 18nW per cm^3. These power levels are relatively low, notably when compared with other harvesting systems [3]; but those outputs belong to non-optimized structures, therefore, higher level of power should be reachable through further studies. These results also hint at a decrease of the energy density as the scale lowers, and was thereafter confirmed by a specific study of the scale effect on the power density (fig. 4). As seen through the power density equation, this decrease is linked to the average speed of the moving part:

$$\text{P} = \frac{E_{col}f_{col}}{Vol} = \frac{1}{2}\frac{\alpha m v^2 f_{col}}{Vol}$$
$$= \frac{1}{2}\frac{\alpha \rho \gamma^3 c^3 v^2 f_{col}}{c^3} = \frac{1}{2}\alpha \rho \gamma v^2 f_{col} \quad (3)$$

Where α and v are respectively the conversion ratio and the average speed defined in equation (2), Vol is the volume of the box, ρ the density of the ball, f_{col} the collision frequency, c is the box side length and γ is the ratio of the diameter of the ball on c. By considering that the collision frequency is higher than the excitation frequency, we furthermore have:

$$v \approx (1-\gamma)c.f_{col} \quad (4)$$

Therefore, although the collision frequency, or the ball speed, has the highest impact on the power density, the size factor c has a negative effect as the scale lowers.

It must be noted that the study of the scale effect also revealed that the conversion factor α was noticeably unaffected by scale change, as long as the PZT plates and the ball's proportions were preserved (fig.5). As a change in the diameter of the ball alone is enough to modify the conversion factor α. It is believed to be a consequence of the almost linearity of the small deformation case, in which both voltage output and Kinetic energy are proportional to the volume of the plate and the ball, respectively. However, this has not been proven in a general case.

As the equation (3) hints at, increasing the size of the ball, hence its mass proved to have a positive effect on the power, since it increases its average kinetic energy. Similarly to PZT cantilevers, the system was also shown to offer an optimal power level at a given electric load. Finally, the model was tested at various frequencies. When the vibration amplitude is a large enough fraction of the backlash between the ball and the walls, at constant acceleration, as would be the case in a natural environment [1], the power generated would increase with the frequency. As was expected from the design, no peak of resonance was observed. Nonetheless, an important resonance phenomenon was observed: depending on the amplitude to backlash ratio, collision frequency changes from almost nonexistent to more than two times the vibration frequency, and the power also changes accordingly (fig. 6).

4.2 Discussion of the optimization possibilities

Initially, an idea was introduced, and then several experiments were executed based on a simple model. However, through this model, many elements of optimization became apparent. Theoretically, the structure should be isotropic in order to optimally absorb vibration no matter the orientation. Although a spherical design may not seem too farfetched, practically, it comes with the risk of the ball rolling inside the PZT box. It is also far more difficult to fabricate than a rectangular design. As a matter of a fact, the best shape is that of a cube. Indeed, trapped in such structure with little backlash, the ball would always be in contact with the walls near their centers, allowing more deformation, while also limiting the probability of it getting stuck in a corner, as would often be the case in a tetrahedral design.
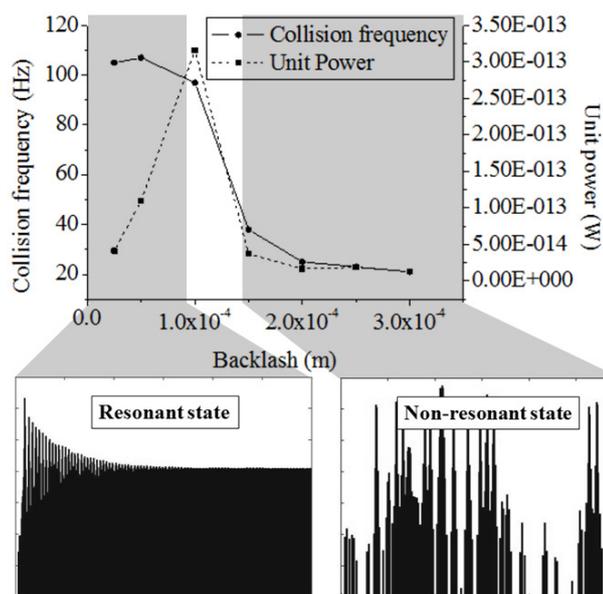

Fig. 6: Top: Simulated graph of the evolution of the collision frequency and the unit power with the backlash (model: 2x2x0.2 PZT plates, 2mm steel ball at 50Hz with 5μm of amplitude). Below, in both states, graphs of the collision speed with time. Each peak corresponds to one collision.

Also, based on the results of the study, one big harvesting unit has been shown to be more powerful than many small ones. Furthermore, the ball inside should be as big and heavy as possible. And finally, the backlash should be small enough to guarantee resonance at the given amplitude of vibration.

5. CONCLUSION

A new design for PZT microharvesting system has been investigated. The principle involves a rigid ball freely moving inside a PZT covered box. Environmental vibration forces the ball into colliding against the PZT walls and consequently generating electric power. Experimentally confirmed simulations were performed under ANSYS and Matlab. The power density of a 2.1x2.1x2.1mm^3 unit and a 0.1x0.1x0.1mm^3 unit were thereby evaluated to respectively 50nW.cm^{-3} and 18nW.cm^{-3} when connected to a 1500Ohm resistor. It, however, appeared that shrinking the device had a negative impact on the power density.

Furthermore, although resonance peaks were not observed in the models, a resonant behavior was confirmed, and sufficiently large excitation amplitude to backlash ratio was identified as the main condition for its realization.

Following this study, a method for fabricating the harvester at a microscopic level, and a more efficient structure will be investigated.

REFERENCES

[1] Roundy S., Wright P. K., Rabaey J., A study of low level vibrations as a power source for wireless sensor nodes, Computer Communications, **Volume 26**, Issue 11, Ubiquitous Computing, 1 July 2003, Pages 1131-1144

[2] Bhushan Bharat 2004 Springer Handbook of Nanotechnology (Verlag, Springer)

[3] Beeby S. P., Tudor M. J., White N. M., Energy harvesting vibration sources for microsystems applications, Measurement Science and Technology, 2006, vol. 17, no 12, R175-R195