# Modeling and analysis of vibration-based MEMS piezoelectric energy harvester for green energy source

SALEM SAADON[a,b*], OTHMAN SIDEK[a]
[a]*Collaborative Microelectronic Design Excellence Center (CEDEC), Universiti Sains Malaysia(USM), Engineering Campus 14300 Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia*
[b]*School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM),14300 NibongTebal,Pulau Pinang, Malaysia*

The wireless sensor network market is growing quickly yet is limited by existing short lifetime batteries. Providing a green, virtually infinite alternative power source to traditional energy sources will significantly expand applications for Wireless Sensor Networks (WSNs) and other technologies, the use of piezoelectric materials to capitalize on the ambient vibrations surrounding a system is one method that has seen a dramatic rise in use for power harvesting. The simplicity associated with the piezoelectric micro-generators makes it very attractive for Micro-Electro-Mechanical Systems (MEMS) applications, in which mechanical vibrations are harvested and converted to electric energy. These micro-generators were designed as an alternative to a battery-based solution especially for remote systems. In this paper we proposed a design and simulation of MEMS-based energy harvested by using ANSYS and COVENTORWARE approaches. The improvements in experimental results obtained in the vibration based MEMS piezoelectric energy harvesters show very good scope for MEMS piezoelectric harvesters in the fields of power MEMS and Green Technology in the future.

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## 1. Introduction

The optimization of power harvesting have been done by several applicable methods in the field of MEMS micro-generators, the first method is by selecting a proper coupling mode of operation. Practically, there are two modes of operation, the first mode called 31mode, in which the excited vibration force is applied perpendicular to the poling direction (pending beam), while the other is called 33 mode, in which the force is applied on the same direction as the poling , described by Johnson et al. [1]. The second method for harvested power improvement is by changing the device configuration by adding multiple pieces of piezoelectric materials to the harvester. By this configuration a highest power can be generated under lower excitation frequencies and load resistances. The series triple layer bimorph constructed of a metallic layer sandwiched between two piezoelectric layers were connected in series electrically. The parallel triple layer bimorph is the same as the previous one but the piezoelectric materials were connected in parallel. The parallel triple layer bimorph had the highest power under medium excited frequencies and load resistances, while the series triple layer bimorph produces a highest power when excited under higher frequencies and load resistances, as described by Ng and Liao [2,3]. A series connection will increases the device impedance as well as improve the output delivered power at higher loads. Other method of increasing the bimorph efficiency was investigated by Jiang *et al.* [4]. Their study focused on a bimorph cantilever with a proof mass attached to its end. Their results showed that, by reducing the bimorph thickness and increasing the attached proof mass will decrease the harvester resonant frequency and produce a maximum harvested power.

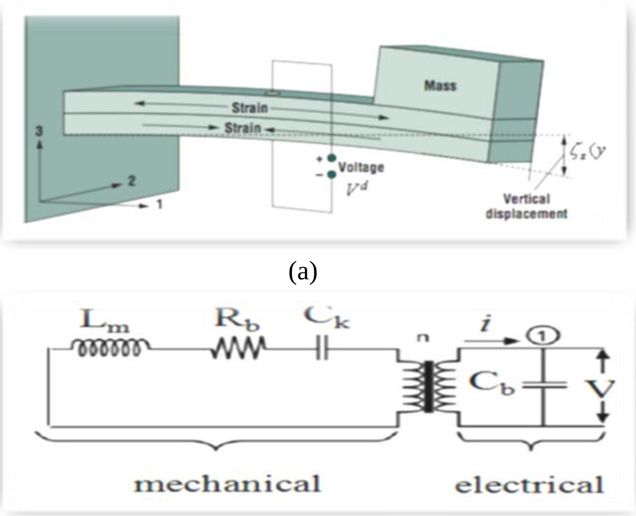
Similarly, Anderson and Sexton [5], found that, by varying the length and width of the proof mass will affect the output harvested power. Cantilever geometrical structures also play an important aspect to improve the harvester efficiency. However, rectangular shaped cantilever structures are the most commonly used in MEMS based piezoelectric harvesters due to their easy implementation and effective to harvest energy from ambient vibrations. The study proposed by Mateu and Moll [6], showed that the triangular shaped cantilever beam, provided with a small end free, will maintain a higher strains and maximum deflections to produce a higher output power than a rectangular beam having width and length equal to the base and height dimensions of the proposed triangular cantilever beam. A trapezoidal shaped cantilever beam was presented and discussed by Roundy *et al.* [7]. They found that, the strain can be more distributed throughout the trapezoidal structure, and stated that, for the same Lead Zirconate Titanite (PZT) volume a trapezoidal cantilever beam can deliver more than twice the energy than a rectangular shaped beam. Similarly, Baker *et al.* [8], experimentally tested a nearly triangular, trapezoidal shaped cantilever beam against with a rectangular shaped beam of the same volume, and found that 30 % more power can be achieved by the trapezoidal beam. Moreover, the following table shows a detailed illustration of the recently obtained results of various types and structures of piezoelectric harvesters proposed by saadon et al [9].

*Table 1. MEMS piezoelectric micro generators with different structures.*

| Ref. | Material | Cantilever type | Amplitude (g=9.81) | Frequency Hz | Delivered Power µW |
|---|---|---|---|---|---|
| [14] | AlN | D31, thin film | 4.0 g | 1368 | 1.97 |
| [15] | PZT | D31, thin film | 2.0 g | 461.15 | 2.15 |
| [16] | PZT | D31, thin film With integrated mass | 1.9 g | 1800 | 40 |
| [17] | PZT | D31, thin film With non-integrated mass | 1 g | 609 | 2.16 |
| [18] | PZT | Thin film array | 0.5 g | 229 | 3.98 |
| [19] | PZT | D33, thin film With interdig. electrodes | 10.8 g | 13900 | 1 |
| [20] | PZT | D31, thin film With interdig. electrodes | 2 g | | 0.123 |
| [21] | PZT | D31 and d33 thin film With interdig. electrodes | 2.5 g<br>2 g | 255.9<br>214 | 2.765<br>1.288 |
| [22] | PZT | D31, thin film With mass and interdig. electrodes | 2 g | 870 | 1.4 |
| [23] | AlN | Different Beams and masses | 2 g | 572 | 60 |

## 2. Piezoelectric harvester modeling

The tasks were performed using various modeling methods as part of this study on MEMS modeling and design of the micro-power harvester as shown in Figs. 1 and 2. Those modeling methods are Lumped-Mass, COVENTORWARE and ANSYS.



(a)

(b)

*Fig. 1. (a) Geometry of a simplified beam [10], (b) Circuit representation of the generator [11].*

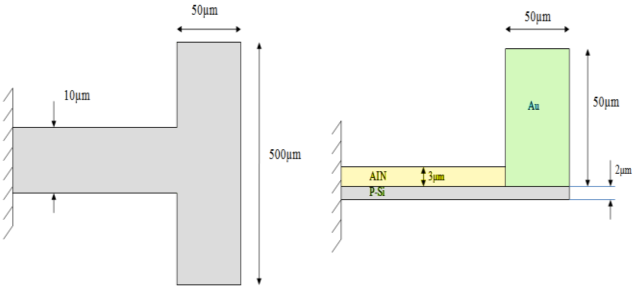


*Fig. 2. Top and side view of a Piezoelectric Micro Power Generator (PMPG).*

## 3. Transient analysis results

In order to gauge the effectiveness of the structure as an energy harvester, motion of the beam and the mass (kinetic energy) must be used as an input to the system to produce a voltage across a load resistance. It is, therefore, the purpose of the transient analysis to simulate the amount of voltage generated in time domain. The following task is to be performed: the obtaintion of the time-history of the seismic mass centre point as it oscillates under a base acceleration of $a(t) = 0.5 \cdot g \cdot \cos(wt)$ where g is the acceleration due to gravity and $w = 2 \cdot \pi \cdot 1200$.

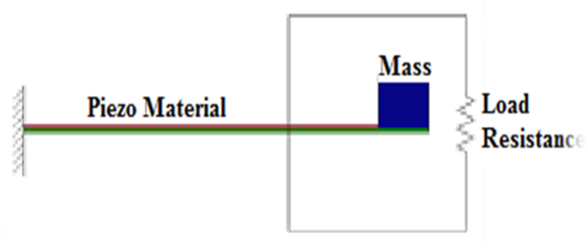


*Fig. 3. Transient analysis schema.*

A load resistance (RL = 10 kΩ) is connected between the leads of the piezoelectric layer to obtain the time-history of the voltage across the load resistance. Use a quality factor (Q) of 15 and start simulation from a point where the MPG is at rest. The schema of the system to be simulated is illustrated in Fig. 3, while the device main structure shown in Fig. 2. In other words, the top electrode of one beam is connected to the top electrode of the other beam, likewise for the bottom electrodes. It has been verified by simulation that connecting the two beams in parallel would produce a larger voltage across the load compared to linking them in series. From an intuitive point of view, the splitting the beam into two parts connected in series, would result in a higher output power. It would be advantageous to divide the beam into multiple narrower beams so that an additional power can be obtained for free. As shown in Fig. 4, the oscillation amplitude predicted by lumped mass model is about 50 % higher than in the cases of ANSYS and COVENTORWARE approaches. However, the envelopes of the three curves are comparable, which means that both have similar damping ratio and quality factor. The ANSYS result seems to have a little more damping as it settles into steady-state before the fifteenth cycle.

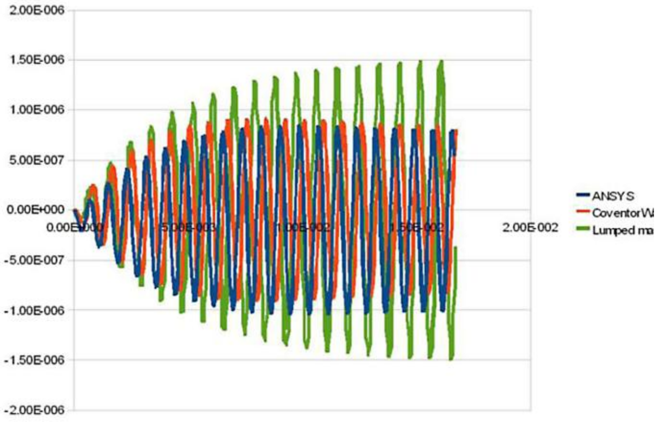


*Fig. 4. Transient analysis of beam deflection.*

The transient voltage results are showed in Fig. 5 (unit for y-axis is Volt). All three approaches (ANSYS, COVENTORWARE and Lumped Mass Model) give similar steady-state amplitudes (+/- 2μV). It is interesting to note that the Lumped Mass Model results in higher vibration amplitude yet the output voltage is similar to the other approaches. The shape of the envelope of the COVENTORWARE result is inconsistent with the other two, but the overshoot is caused by the fact that the forcing frequency is further away from its resonant frequency. Therefore this is not a great concern. Overall, all three approaches show that they can be used to predict the efficiency of the piezoelectric MPG.

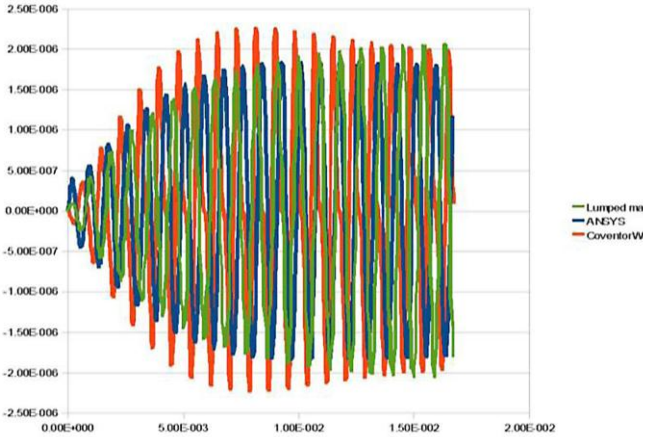


*Fig. 5. Transient analysis results – voltage.*

It should be pointed out that the resulting power using a 10 kΩ load resistance is in the order of pW. Simulations using both COVENTORWARE and ANSYS show that the power would increase if a larger load is used. It is found that the optimum load resistance is around 1GΩ. The power produced in that case is in the μW range.

## 4. Conclusions

We have described a piezoelectric energy harvester with transient analyses under different methods such as ANSYS, COVENTORWARE and Lumped Mass Model. All three models ANSYS, COVENTORWARE, Lumped Mass Model are approximately matched in the transient response.

After around 12.5 ms, there is a stable oscillation with respect to time, the oscillating voltage amplitude being around ± 2 μV. One difference is that the envelope of the Lumped Mass Model is still increasing after 15 ms. This could be the problem of the damping ratio that is not matched to the system and therefore the voltage keeps increasing. Also, the result in COVENTOREWARE has a bit overshoot effects simply because its model may not be at the exact resonant frequency. However, this minor problem could be fixed by slightly shifting the accelerating frequency to a real resonant frequency. The models for ANSYS and COVENTORWARE are approximately the 0.8 μm, which are quite similar to the static simulation result. However, the efficiency of Lumped Mass Model is around 50 % higher, which does not match with the static result. The envelopes are all roughly the same. The change of the output power with respect to load resistance is similar to both ANSYS and COVENTORWARE.

The optimal load is around 1 G Ω. and its maximum output power is around 10 pW which is quite small for a real application. It is absolutely a very good reference for MEMS designers to build up a more complicated piezoelectric micro-power generator or the considerations with different perspective approaches to improve the harvested power.

## 5. Future work

Our future work is to design and fabricate a novel vibration-based MEMS micro power harvesting device consisting of piezoelectric cantilever type together with interface power conversion circuitry. This is expected to provide the optimal desired dc output power characteristics with high efficiency satisfying all the desired parameters and also maintain an output power that can be used to power wireless sensor networks instead of the conventional batteries.

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[*] Corresponding author: salem@cedec.usm.my