Multi-Frequency Energy Harvesting Using Thick-Film Piezoelectric Cantilever

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***Abstract*— Due to the fact that the ambient vibration sources are random and unpredictable, the design of energy harvesters responsing to multi-freuqncy is desirable. In this paper, an array lead zirconate titanate (PZT) thick-film cantilevers were designed and fabricated to demonstrate the possibility of harvesting vibration energy from different frequencies. Two configurations of multi-cantilever were fabricated in a form that elevated from the substrate as free-standing structures. One having six cantilevers of constant width but different lengths and another having five cantilevers of constant length but different widths. The experimental results show a magnitude of voltage at around 70 mV in a range of freqnecy between 220 Hz to 520 Hz which is in a good agreement with simulation results.**

***Keywords*— Energy Harvesting, Thick-Film, Free-Standing Structure, Piezoelectric**

I. INTRODUCTION

There are a few issues concerning cantilever-type energy harvesters. Of significance is the narrow bandwidth of frequencies, where a small change (±2 Hz) in excitation frequency will lead to a drastic drop in the output power (-3 dB). This is due to the high *Q*-factor of a piezoelectric cantilever structure, which is typically greater than 100. This characteristic is favorable when operated with a vibration source of constant excitation frequency. Ambient vibration sources, however, are unpredictable, and therefore a wider bandwidth of operation is desirable.

One of the ways to increase operating frequency is by utilizing a self-tuning mechanism, where the energy harvester can tune its resonant frequency to match the vibration source on which it is mounted, thereby optimizing its electrical output. This can be done by altering the parameters of the generator such as the mass, length or the stiffness of the system. Tunable energy harvesters can be classified into two categories; active and passive [1] or intermittent and continuous as described in [2]. Generally, there are two possible methods to increase the operating frequency range; tuning and bandwidth widening [3].

In this paper, bandwidth widening method based on multi-frequency response of cantilever structures was studied. These structures consist of an array of free-standing cantilevers [4] fabricated in a monolithic manner using thick-film technology, which do not require manual assembly of active mechanical structures to the electronic circuits as what the traditional thick-film resonant devices do [5]. The active mechanical structure is a sandwich layer of lead zirconate titanate (PZT) and silver/palladium (Ag/Pd) as the upper and lower electrodes [6]. The active resonant structure is free from clamping to the substrate therefore it is flexible to move in transverse direction at low frequency levels which match to the ambient vibration.

The natural frequency of a cantilever structure can be altered by changing its dimensions and mass according to Bernoulli-Euler equation. When operated in an array of cantilevers with small differences in lengths or masses, they can harvest optimum electrical energy collectively from each of the cantilevers over a wider bandwidth of excitation frequencies as described by Sari *et al* [3].

As the piezoelectric coupling is small, the mechanical performance of the cantilever in response to harmonic excitation can be studied and simulated using finite element method analysis softward, ANSYS™.

Two designs of multi-cantilever systems were fabricated and tested. One of which is a multi-cantilever with six cantilevers (or fingers) of different lengths from 15 – 20 mm. These cantilevers having a uniform width of 5 mm and thickness of 85 μm, produce a range of operational frequency of 240 – 500 Hz. The other design is a multi-cantilever with five fingers of different widths from 2 – 10 mm, having a uniform length of 20 mm and thickness of 85 μm, which has an operation range of 280 – 350 Hz. The continuity level of the operational frequency increases with proof masses attached at the tip of the cantilevers. The experiment results show that the devices have the potential to be developed as energy harvesters with practical application.

II. PIEZOELECTRIC CANTILEVER MODEL

Generally, the base excited harmonic motion is modelled as a spring-mass-damper system with the equation motion,

$$M\ddot{x} + b(\dot{x} - \dot{y}) + k(x - y) = 0 \qquad (1)$$

where y denotes the displacement of the base and x the displacement of the mass from its static equilibrium position. The vibration body is assumed to have a harmonic motion,

$$y(t) = Y \sin \omega t \qquad (2)$$

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From the Bernoulli-Euler equation derivation, a thin cantilever beam with one end clamped and the other end free, the natural transverse vibration can be written as,

$$f_i = \frac{v_i^2}{2\pi\sqrt{2}} \left(\frac{h_T}{l_b^2} \right) \sqrt{\frac{e_T}{\rho}} \tag{3}$$

where v_i is a coefficient related to boundary conditions, h_T is the total thickness of the cantilever beam, l_b is the length of the cantilever beam, e_T is the resultant elastic modulus and ρ is the density of the structure.

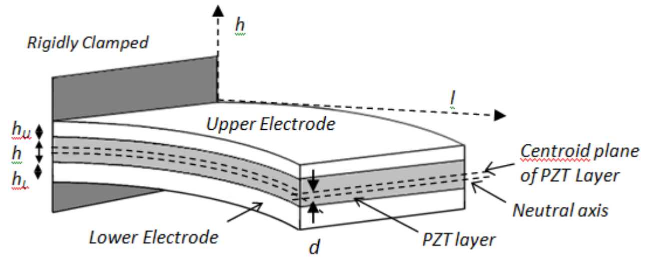


Fig. 1 A schematic diagram of a sandwiched piezoelectric cantilever

The cantilever structures are fabricated in the form of “sandwiched structure” as shown in Fig. 1, whereby the piezoelectric material is bound in between upper and lower electrodes. The distance from the centroid of the PZT layer to the neutral axis of a composite structure having thickness of piezoelectric of h, lower electrode, h_L and upper electrode, h_U is given by,

$$\beta = \frac{1}{2}h - \frac{h^2 + n_E(h_L - h_U + 2hh_L)}{2(h + n_E(h_U + h_L))} \tag{4}$$

where n_E is the ratio of elastic modulus of the electrode layer and the piezoelectric layer. When the neutral axis is in coincident with the centroid of the piezoelectric materials, no resultant stress will be acting on the neutral axis over the cross section area of the active material. As a result, no electrical charge will be produced, therefore it is desirable to increase the β factor in order to generate more electrical output.

The output voltage when the piezoelectric is excited under harmonic oscillation can be estimated by equation (5) deduced from Round’s dynamic model [7]. At resonant frequency, ω_r, the amount of voltage generated can be simplified in complex equation as,

$$V = \frac{3}{4} \frac{j e_T d_{31} h_{PZT} \beta a_{in}}{\varepsilon l_b^2 \left\{ \zeta_T \omega_r^2 - j \left[\frac{\omega_r^2 k_{31}^2}{2} + \frac{\zeta_T \omega_r}{R C_p} \right] \right\}} \tag{5}$$

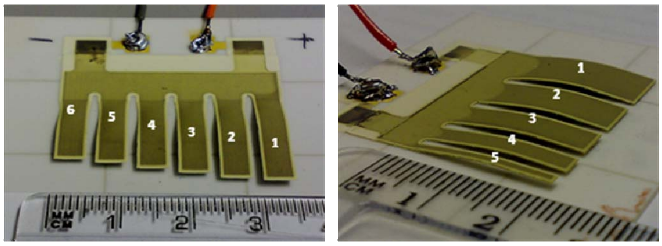
where e_T is the resultant elastic modulus, h_{PZT} is the thickness of the piezoelectric materials, β is the distance from the centroid of the layer of PZT to the neutral axis of the structure, a_{in} is the excitation acceleration, l_b is the length of the beam, ζ_T is total damping ratio of the cantilever structure, R is the resistive load and C_p is the capacitance of the piezoelectric materials. d_{31} and ε are the piezoelectric charge and dielectric constant of the piezoelectric material respectively.

Although the model is somewhat oversimplified, it does give a reasonable good approximation for the voltage generated and will be used to compare with the experimental results in this work.

III. FABRICATION AND EXPERIMENTAL SET-UP

Conventional micro-electro-mechanical systems (MEMS) are fabricated in miniature sizes in the range of micrometers. The smaller the size of the devices, result in the smaller the generation of electrical power, which may not be useful for powering micro-system. For the application of energy harvesting, the minimum requirement of output power is about 50 µW [8].

Two configurations of cantilever arrays were designed and fabricated as shown in Fig. 2. One of which is an array of cantilever with six fingers having different lengths and the other is having five fingers having different widths. The dimensions of the devices are designed according to the limitation of screen-printing process and thick-film processing technique.



(a) (b)

Fig. 2 An array of cantilever with (a) six fingers having different length and (b) an array of cantilever with five fingers having different width

Both of the configuration having same thickness of 50 µm and an elevated gap height from the substrate of 1.2 mm. Configuration 1 having standard width of 5 mm, while configuration 2 having standard length of 20 mm. The variety of length for configuration 1 and width for configuration 2 are listed in Table 1.

The devices were tested on a vibrometer as shown in Fig. 3, at a harmonic excitation over a range of different frequencies close to the resonant frequency of the cantilevers at a constant acceleration level. The acceleration level is a function of the frequency according to $a_{in} = Y\omega^2$. To maintain the acceleration level, therefore needs a feedback system. An accelerometer in the vibrometer measures the actual value of the frequency and acceleration level and is feedback into a comparator to compare with the set point. A processed signal is then generated and amplified to drive the vibrometer to produce the desired acceleration level at a given frequency.

TABLE I
DIMENSIONS OF THE CANTILEVER ARRAY

	Finger no.					
Config. 1	1	2	3	4	5	6
Length (mm)	20	19	18	17	16	15
Config. 2						
Width (mm)	10	8	6	4	2	NR*

NR =Not relevant as Configuration 2 consists of 5 figures.

Fig. 3 Device under test on a vibration generator

IV. RESULTS AND DISCUSSION

The results of the simulation with ANSYS^{TM} show the stress distribution plots for both of the configurations as shown in Fig. 4. For each of the structures, the stress is concentrated at the clamped end of the cantilevers near to the base of the structure when it is excited to their resonant frequencies. For the case of configuration 1 as shown in Fig. 4 (a), a maximum stress of about 1.1 MPa was calculated when excited at 211 Hz, which is the resonant frequency of the longest cantilever. The other cantilevers on this array have a distribution of stresses with magnitudes below the maximum level. The maximum stress distribution pattern shifts toward the second, third (and so on) cantilever, when excited to higher resonant frequencies that are matched to each individual cantilever.

Fig. 5 shows a comparison of the cantilever array of configuration 1 with individual cantilever having similar lengths. The total magnitude of stress of cantilever array appears to be less than that of the individual cantilevers with respective lengths. A slight frequency shift toward lower values was also noticed in the comparison. With no interaction of piezoelectric effect on the simulation, the results can be explained as a pure mechanical damping interaction between all the cantilevers in the configuration.

The equation for a pure bending cantilever beam under harmonic base excitation (3) does not predict a modal frequency dependence on the width of the cantilever. From ANSYS^{TM} simulation results, however, it can be shown that the resonant frequency of the cantilever array of configuration 2 having five fingers with different widths varied between 250 – 400 Hz, with optimum response at around 300 Hz, as shown in Fig. 6. This dependence is due to the coupling interaction between the fundamental and higher order modes of vibration of each individual cantilever.

Fig. 7 shows the experimental results of the cantilever array of configuration 1 at an excitation frequency of 220 Hz to 520 Hz at a constant acceleration of about 5 m/s^2. The output voltages were measured when driving a resistive load of 25 kΩ. The performance of the cantilever array was compared to a reduced number of cantilever by breaking off one by one began with the longer to shorter cantilever of the array. It is noticed that, the peak of the output voltage increases as the number of the cantilever decreases. This is due to the loading effect of the piezoelectric material of the cantilever array, which appear to be electrically connected in parallel.

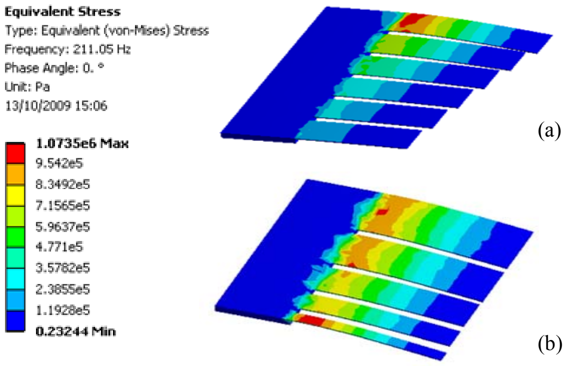


Fig. 4 ANSYS^{TM} simulation results showing stress distribution on an array of cantilever for (a) configuration 1, with different lengths and (b) configuration 2, with different widths.

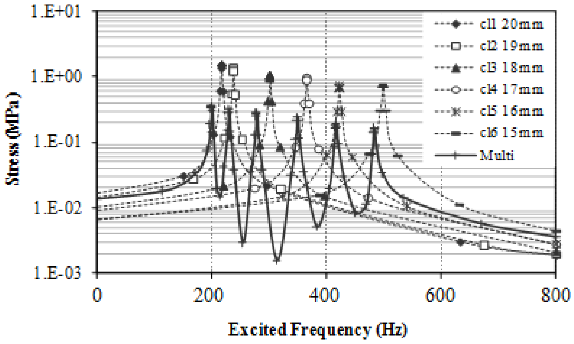


Fig. 5 Average stress of cantilever structure as a function of excited frequency for an array of cantilevers with different lengths (configuration 1) compared with individual cantilever with different lengths. "cl" stands for cantilever length and "Multi" stands for multi-cantilever (configuration 1).

In another experiment, the cantilever array of configuration 2 (having different widths) was excited to a range of frequency between 200 Hz to 600 Hz and the performance of the energy harvester is shown in Fig. 8. It is noticed that the pattern of the frequency peak is irregular and concentrated at around 350 Hz, which is coincident to the resonant frequency of finger 3 of configuration 1, having a standard length of 20 mm and width of 5 mm. It is also noticed that, there is another resonant peak at around 520 Hz in the frequency excitation range. Therefore, it can be concluded that the width of the cantilever is influencing the performance of the cantilever array at some extend but not widening the operating frequency of the energy harvester. In the order hand, the narrower the cantilever the more susceptible it would be to excite to higher order vibration mode. This has to be taken into account when fabricating energy harvesting devices using brittle and fragile ceramic piezoelectric materials.

V. CONCLUSION

The purpose of this paper is to demonstrate the possibility of using thick-film piezoelectric devices arrange in an array of cantilever with different dimensions which are able to response to a range of frequencies. These muti-frequency energy harvesting devices is potentially one of the solutions for harvesting energy from random and unpredictable ambient vibration sources. The experimental results show a good agreement with the simulation results in responding to the performance of the array of cantilever at a range of frequency from 200 Hz to 600 Hz.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of this work by Universiti Teknikal Malaysia Melaka (UTeM) on short term research grant no. PJP/2010/FKEKK(24C)S764.

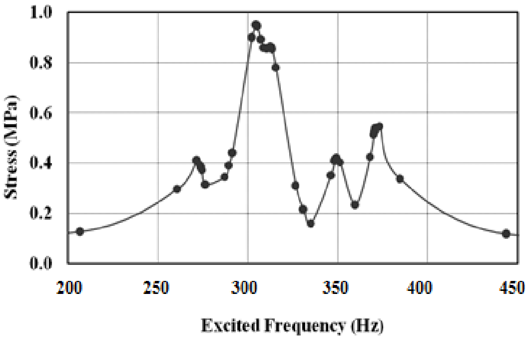


Fig. 6 Maximum stress as a function of excitation frequency for configuration 2 for the cantilever array with five cantilevers having different widths.

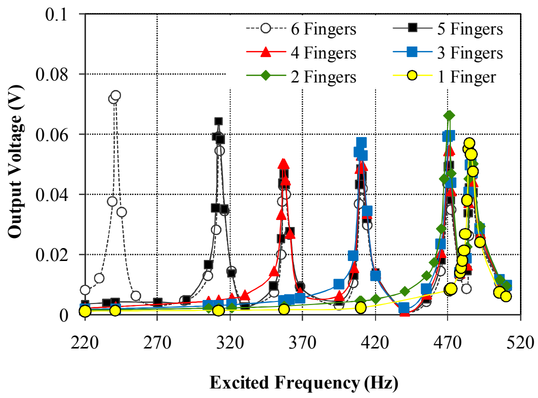


Fig. 7 Experimental results of the output voltage (at a resistive load of 20 kΩ) at an excitation frequency in the range of 220 to 520 Hz for the cantilever array of configuration 1.

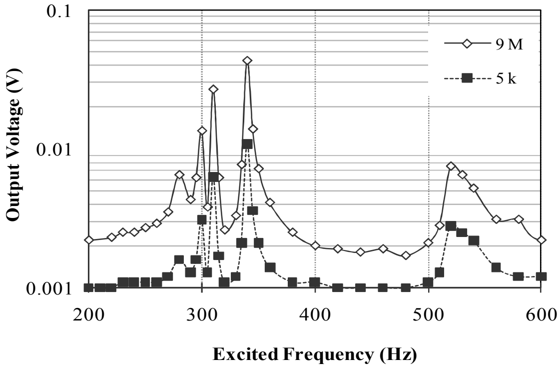


Fig. 8 Experimental results of the output voltage at an excitation in the range of 200 – 600 Hz for the cantilever array of configuration 2 at the resistive load of 5 kΩ and 9 MΩ.

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