HARVESTING ELECTRICAL CHARGE FROM AMBIENT VIBRATION USING PIEZOELECTRIC MATERIALS

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ABSTRACT. *Nowadays the energy source for portable electronic devices heavily depends on battery which has limited lifetime and contributes to environmental pollution after discarding it. This has created an environment impact to the soil and water. A green solution to reduce excessive pollution from battery usage is suggested in this paper with the use of piezoelectric materials to convert ambient vibration into the required electrical energy. The piezoelectric material is adhered to a cantilever beam to form a piezoelectric bender and its analytical model with base excitation is first established to study the effect of the structural and connecting configurations of the constructed benders on the harvested electric charge. The model predicts that the single-active layer piezoelectric bender harvests about 1.6 times of electric charge and two-active layer piezoelectric bender in parallel connection harvests two times, than that harvested by two-active layer piezoelectric benders in series connection. The experimental results comply with the theoretical predications. Among all the combinations, the two-active layer piezoelectric bender in parallel connection is concluded the optimum configuration for electrical charges harvesting. It is also shown in this paper the application of piezoelectric charge harvester to light up LED. This shows the potential application of piezoelectric charge harvester to replace battery usage that may reduce heavy mental pollution to the environment.*

KEYWORDS. Electric charge generation, piezoelectric materials, single-active layer bender, two-active layer bender.

INTRODUCTION

Almost all the mobile electronics devices (such as wearable computers, MP3 players and wireless sensing nodes) are designed to battery-powered embedded. As such, the operation time for the devices fully relies on the life span of the battery. Once the battery runs out of energy, replacement is required in order to continue the operation of the devices. This is difficult for certain application such as for wireless transmitter that placed at animal’s body to trace its migration in forest (Guo et al, 2006). Other than the trouble with battery replacement, the heavy metals (such as Cadmium and Lead) released from the waste battery will pollute the soil and underground water after it has been deposed into the land (Ma, 2006; Nie and Niu, 2000; Eklund, 1995) which further contribute to other source of pollutions described in (Mohd. Harun Abdullah, 2007; Caroline Melissa Payus, 2007; Ma, 2006; Baba Musta et al, 2004; Nie and Niu, 2000; Eklund, 1995; Hebel et al, 1976). Due to the fact that mechanical vibration is available everywhere in daily life, (Tabesh and Frechette, 2010; Lee et al, 2007; Xia et al, 2006) have suggested to use piezoelectric materials to convert ambient vibration into electrical energy for the devices. As compare the common ways of energy generation (such as electromagnetic induction generation and electrostatic charge generation), the use of piezoelectric material provides the benefits of simple mechanism and small size in setup structure (Jedol Dayou et al, 2009; Sodano et al, 2002).

Under vibration excitation, the piezoelectric materials experiences mechanical stress that distorts its internal dipole moments. As a result, electrical charges are produced. Several works reported the charges production and harvesting using piezoelectric material in the form of cantilever beam (Jedol Dayou et al, 2009; Umeda et al, 1996). All these works show the capability of the materials to harvest electric charges from the ambient vibration.

The theory behind cantilever type piezoelectric materials is well known and the parameters affecting the generation of electric charge are the mode of vibration, method of excitation, piezo stress and strain constants as well as dimensions and Young’s modulus of the materials (Platt et al, 2005). However, the harvesting performance due structural configuration (single-active layer and two-active layers) and connecting configuration (series and parallel connections) of the piezoelectric cantilever beams have not been considered in any reported research works.

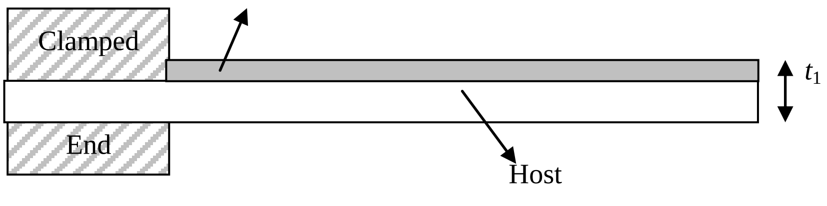
In this paper, the effects of the structural and connecting configurations of the piezoelectric materials, in the form of cantilever bender, on the harvesting of electric charges are studied. The analytical model is first formulated. After that, computer simulations are then carried out to visualize the effects of these parameters. It is then verified with the experimental results.

Modeling Of Piezoelectric Charge Harvester

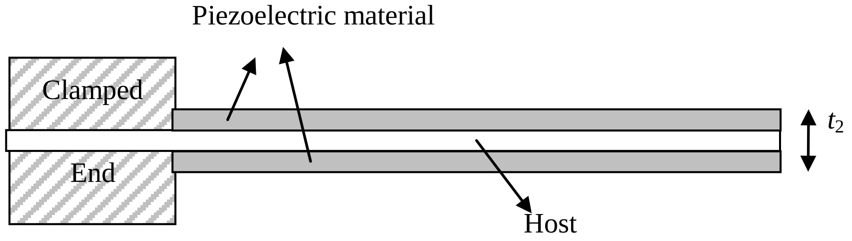
A single-active layer bender and a two-active layer bender as shown in Fig. 1 are used in this investigation with base excitation. When an external force, F, is applied to the base of the bender, electric charges, Q, will be harvested on the piezoelectric material and they can be obtained by integrating the electric displacement, D_3, to its overlapping area which is

$$Q = \int_0^w \int_0^L D_3 dydx , \qquad (1)$$

where L and w are the length and width of the piezoelectric bender respectively.



(a) Bender with single-active layer.



(b) Bender with two-active layers.

Figure 1. Schematic diagrams of two configurations of the piezoelectric bender.

Let *n* be the number of benders (when more than one bender are used) connected in either series or parallel. The electrical charge harvested from *n*-parallel and *n*-series for both the single-active layer and the two-active layer benders are expressed as:

$$Q_{\text{single},n-parallel} = \frac{3nAB(1-A+AB)}{{t_1}^2 k_1} g_{31}\varepsilon_r\varepsilon_0 L^2 F \cdot \tag{2}$$

$$Q_{\text{single},n-series} = \frac{3AB(1-A+AB)}{{t_1}^2 k_1} g_{31}\varepsilon_r\varepsilon_0 L^2 F \cdot \tag{3}$$

$$Q_{two,parallel,n-parallel} = \frac{12n(1+A)}{{t_2}^2 k_2} g_{31}\varepsilon_r\varepsilon_0 L^2 F \text{ ,} \tag{4}$$

$$Q_{two,parallel,n-series} = \frac{12(1+A)}{{t_2}^2 k_2} g_{31}\varepsilon_r\varepsilon_0 L^2 F \text{ ,} \tag{5}$$

$$Q_{two,series,n-parallel} = \frac{6n(1+A)}{{t_2}^2 k_2} g_{31}\varepsilon_r\varepsilon_0 L^2 F \cdot \tag{6}$$

$$Q_{two,series,n-series} = \frac{6(1+A)}{{t_2}^2 k_2} g_{31}\varepsilon_r\varepsilon_0 L^2 F \cdot \tag{7}$$

where

$$k_1 = h_1(1-A+AB)\left(1+Y_{piezo}{g_{31}}^2\varepsilon_r\varepsilon_0\right) - 3(1-A)A^2B^2Y_{piezo}{g_{31}}^2\varepsilon_r\varepsilon_0 , \tag{8}$$

$$k_2 = 4h_2\left(1+Y_{piezo}{g_{31}}^2\varepsilon_r\varepsilon_0\right) - 3Y_{piezo}{g_{31}}^2\varepsilon_r\varepsilon_0(1-A)(1+A)^2 , \tag{9}$$

$$h_1 = 1 + A^4(1-B)^2 - 2A(2A^2-3A+2)(1-B) , \tag{10}$$

$$h_2 = 1 - A^3 + A^3B , \tag{11}$$

t_1 and t_2 are the total thicknesses for single-active layer bender and a two-active layer bender, respectively (see Fig. 1), Y_{piezo} is the Young's Modulus of the piezoelectric material, g_{31} is the piezo stress constant, ε_r and ε_0 are the relative permittivity of the piezoelectric material and the permittivity of vacuum, respectively, and $\varepsilon_0 = 8.85 \times 10^{-12} Fm^{-1}$.

In one complete vibration, there are 2 bendings on each piezoelectric bender. Electric charge, *Q*, is produced in each bending and stored in capacitor *C*. If the bender is vibrating at the frequency of *f* Hz, and the bender takes *t* second to charge up the capacitor to a voltage *V*, the total electric charge stored in the capacitor at this voltage *V* can be obtained by

$$Q_{total} = CV \text{ .}$$

(12)

Each bending takes time of $T = 1/(2f)$ second and each t second has x number of bendings. Thus, x can be expressed as

$$x = 2ft\ . \tag{13}$$

Therefore, the electric charge harvested per bending can be calculated as

$$Q = \frac{Q_{total}}{x} = \frac{CV}{2ft}\ , \tag{14}$$

MATERIALS AND METHODS

To investigate the electric charge harvesting performance of the piezoelectric bender in both the simulations and experiments, the external force applied to the base of the bender was set to be 1 x 10^{-3} Newton. The length and width of the piezoelectric bender used is 97 *mm* X 11 *mm*, respectively. ε_r is 13 for the selected piezoelectric material, and polypropylene was selected as the host. The Young's Modulus ratio (ratio of the Young's Modulus of the host to the Young's Modulus of the piezoelectric film) B of the bender is 0.3. Thickness ratios (ratio of the host thickness to the total bender thickness) A for the single-active layer bender and the two-active layer bender are 0.704 and 0.543, respectively.

The harvested electric charges from vibration were predicted by simulating the analytical equations (2) – (7) for all configurations of the piezoelectric benders. The experiments were carried out at the bender's resonant frequency with a fixed base excitation from the shaker, which was powered up with the frequency generator, to all investigated configurations of the piezoelectric benders. The maximum bender number n used in each of the configurations in the experiment was 3. The experimental setup is shown in Fig. 2. Capacitor was used as a storage device and its voltage was measured by a high internal resistance voltmeter. The charging time t to reach steady voltage V was also recorded for every investigation. The electric charge harvested Q, per bending for each setup was calculated by equation (14).

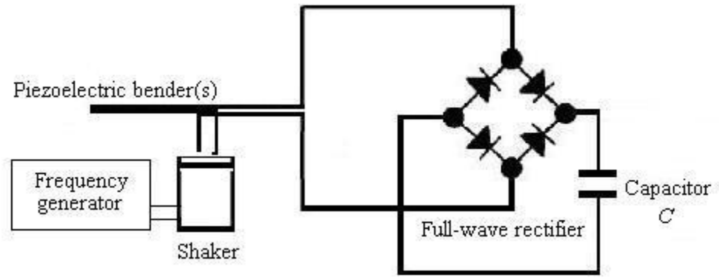


Figure 2. Experimental setup of electric charges and energy harvesting with piezoelectric bender.

In order to determine the rate of electric charge harvesting with various n-parallel and n-series for single-active layer benders and two-active layer benders in both parallel and series connection, an electronic device as shown in Fig.3 was used in connection with the storage capacitor. This device is a pulse-light emitting circuit. When the voltage across the capacitor meets its threshold value (i.e. 1.0 *V*), the capacitor will be discharged through the LED in the circuit. The comparison between the theoretical predictions and the experimental works in electric charge harvesting with all configurations of the piezoelectric bender was then performed at the last stage.

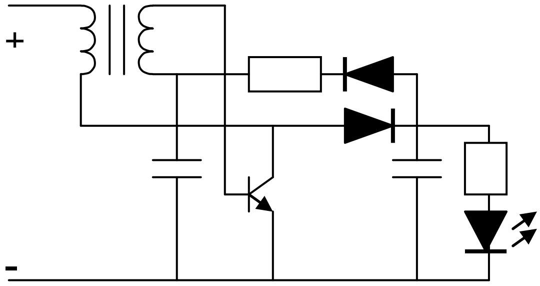


Figure 3. Schematic diagram of pulse-light emitting circuit.

RESULTS AND DISCUSSION

Simulations: Computer simulations for both the benders of single-active layer and the two-active layer with parallel and series combination up to $n = 5$ were performed using the analytical equations (2) – (7). The simulation results for the electric charge generating are shown in Fig. 4.

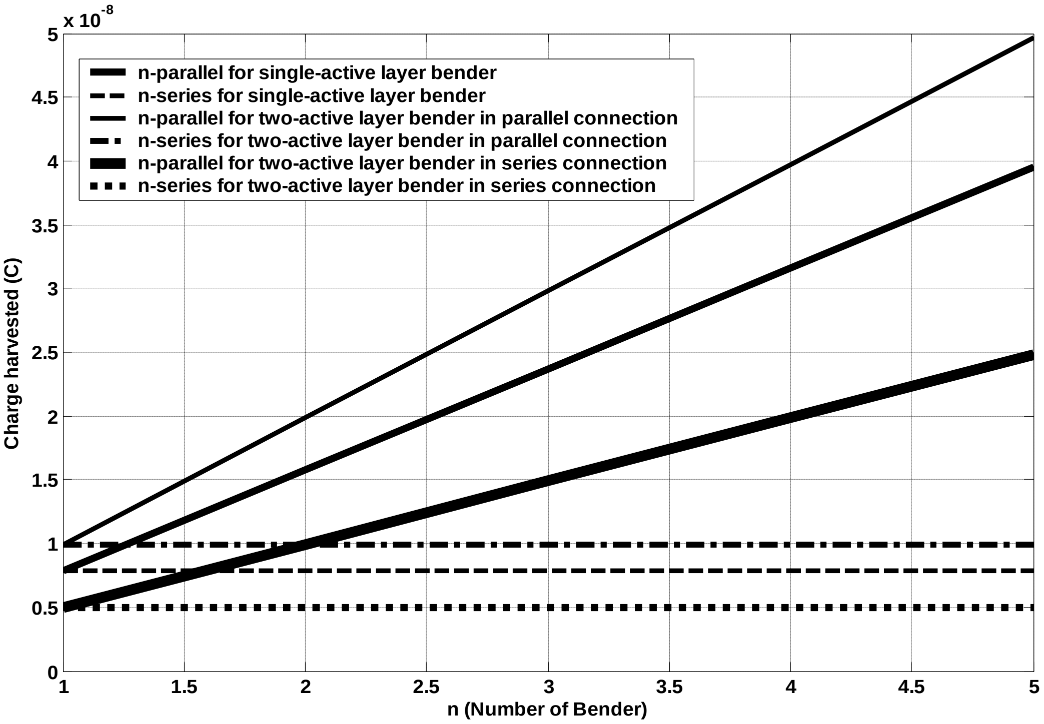


Figure 4. Simulation result of harvested electric charges with various numbers of piezoelectric benders.

Experiments: The experimental results of the generated electric charge for *n*=1 to *n*=3 with various configurations of piezoelectric benders are shown in Fig. 5.

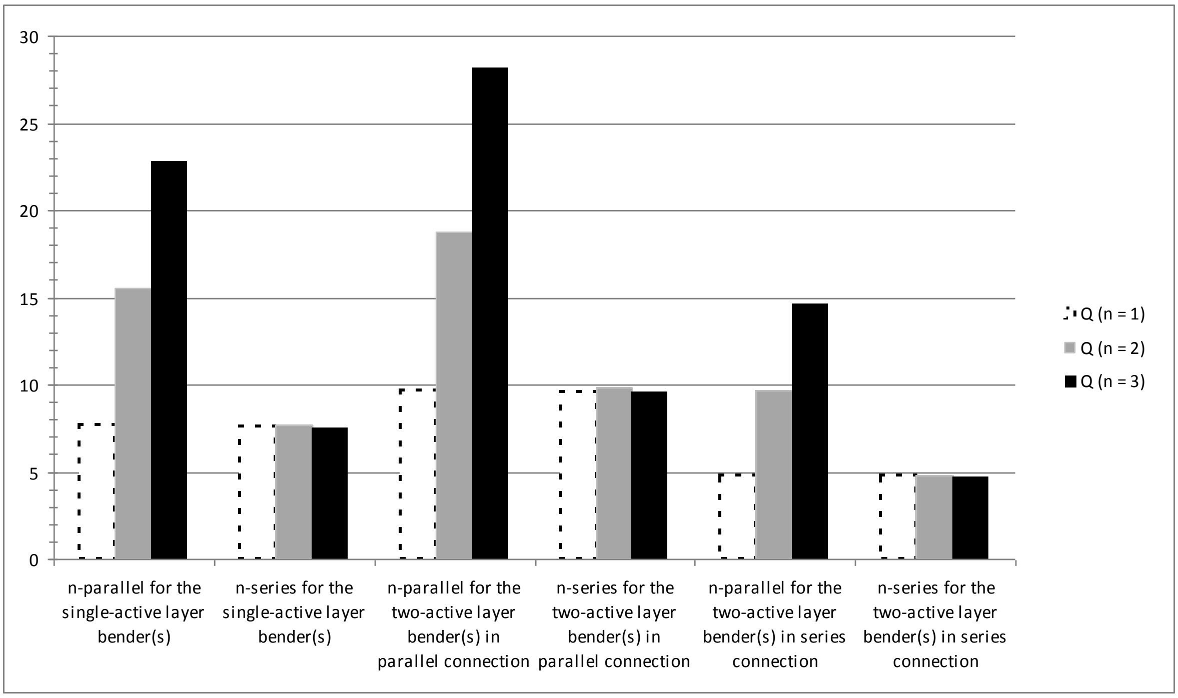


Figure 5. Experimental result of the harvested electric charge (units in nano Coulombs, *nC*) for *n*=1 to *n*=3 with various configurations of piezoelectric benders.

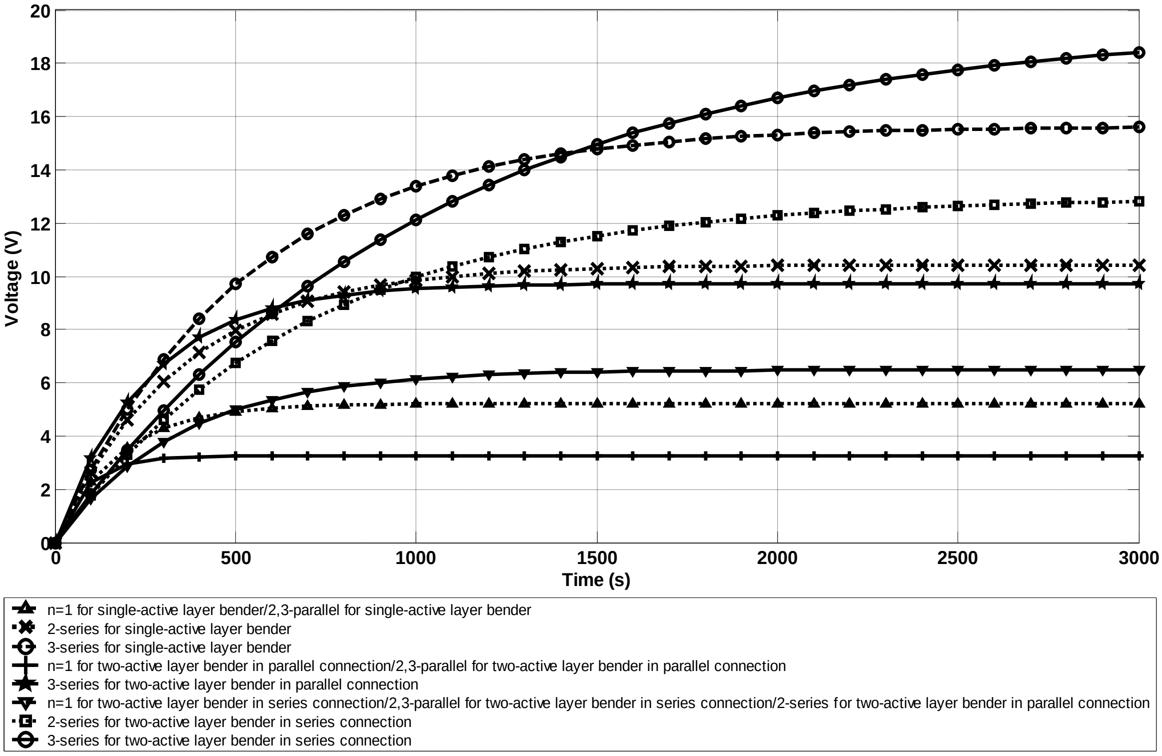


Figure 6. Charging curves to maximum voltage of *n*-parallel and *n*-series for single-active layer benders and two-active layer benders in both parallel and series connection.

The charging time to reach steady voltage was recorded and shown in Fig. 6. Fig. 7 shows the charging results to reach the threshold voltage (1.0 *V*) of the pulse-light emitting circuit with time for all the configurations. The LED emits light in single pulse mode as shown in Fig. 8.

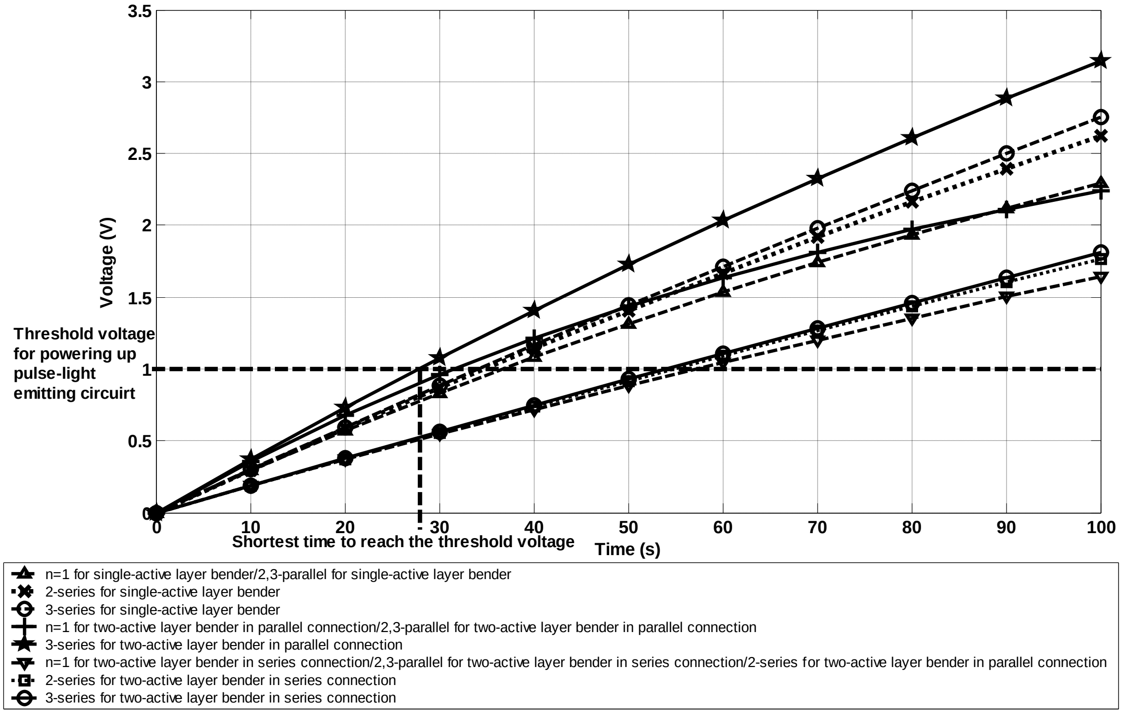


Figure 7. Charging curves to threshold voltage of *n*-parallel and *n*-series for single-active layer benders and two-active layer benders in both parallel and series connection.

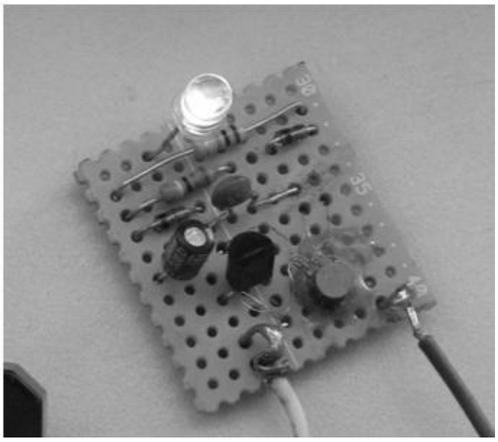


Figure 8. The LED emits light in single pulse mode during discharging of the storage capacitor.

It was found that the experimental results (Fig. 5) were agreed with the simulations (Fig. 4) within small discrepancy of less than 10 %. All the charges generated from *n*-series were constant for the same type of configuration and all the charges generated from *n*-parallel were directly proportional to the bender number, *n*. The charges generating with the two-active layer bender in parallel connection were twice of that with the two-active layer bender in series connection. The charges generating with the single-active layer bender were

1.6 times more than that with the two-active layer bender in series connection.

In Fig. 6, all the voltages of *n*-parallel were constant for the same type of configuration and all the voltages of *n*-series are directly proportional to the bender number, *n*. The voltage output from the two-active layer bender in series connection was twice of that with the two-active layer bender in parallel connection. The voltage from the two-active layer bender in series connection was 1.6 times more than that from the single-active layer bender.

In Fig. 7, it can be seen that the charging rates for *n*-series connection were constant for the same type of configuration and whereas the rates for *n*-parallel were directly proportional to the bender number, *n*. The rate with the two-active layer bender in parallel connection was twice of that with the two-active layer bender in series connection. The rate with the single-active layer bender was about 1.6 times more than that with the two-active layer bender in series connection.

CONCLUSION

In this paper, the analytical model with base excitation to study the effect of the structural and connecting configurations of the given piezoelectric benders on the harvesting of electric charge was established. From the results of the experiment, the harvested electrical charges with the two-active layer bender in parallel connection were twice of that with the two-active layer bender in series connection. On the other hand, harvested electrical charges with the single-active layer bender were 1.6 times more than that with the two-active layer bender in series connection. These experimental results were agreed with the predictions from simulation within acceptable uncertainties. Among all the combinations of structural and connecting configurations, the two-active layer piezoelectric bender in parallel connection is concluded to be the optimum configuration for harvesting electrical charges. As a result, this configuration provides the highest LED flashing rate in a pulse-light emitting circuit under the steady vibration condition. This work has also demonstrated the potential of replacing the battery usage with the piezoelectric harvester.

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