

# Split-electrode piezoelectric scavengers for harvesting energy from torsional motions

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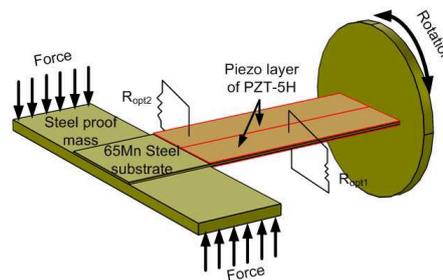
**Abstract.** As most of cantilever scavengers are limited in working in bending mode, it motivates the idea to develop a device that can work with torsional motions. From the finite element analysis, it is found that the torsional modal frequency is near the bending mode frequency, which makes it possible to widen the working frequency range. By using the coupled piezoelectric-circuit finite element method, the harmonic performances of bulk and split electrode devices are quantitatively characterised. The maximum output voltages and power for split-electrode devices are calculated to be 26.7V, 29.35V and 0.023W, which present much more advantages over the bulk-electrode device (1.21V and 43.3 $\mu$ W correspondingly). In this analysis, it is deduced that the cancelling effect occurs across the surfaces of bulk electrodes. For further validation, transient analysis is conducted and it proved that average output power of split-electrode device is almost 25.35% higher than that in bulk electrode device.

## 1. Introduction

One common form of energy harvesting devices is the cantilever structure as it is easily matched to ambient vibration frequency for maximum output power. The coupled piezoelectric-circuit finite element model (CPC-FEM) in ANSYS software to develop a sandwiched bimorph cantilever structure was reported, which could calculate the output power directly [1]. A plucked piezoelectric bimorph for knee-joint energy harvesting has also been developed. [2] The device is able to vibrate at resonance even it is excited at much lower frequency by the frequency up-conversion mechanism. However, these devices are still limited in just working in bending mode. Cheng et al proposed a circular cylindrical ceramic shell for harvesting power from angular motions based on torsional mode. [3] Abdelkefi studied the energy harvesting mechanism from a tuned bending-torsion system by adjusting the asymmetry of the tip masses. [4] Recently, Cha et al. [5] analysed underwater energy harvesting from torsional excitation which utilized similar mechanism with our previous work [6].

A model of the split electrode energy harvester is built in this paper. As shown in figure 1, the steel substrate is sandwiched by PZT-5H piezo layers, with electrodes separated into two equal sizes on both top and bottom surfaces. One end of the cantilever beam is fixed to a rotator and the other end is bonded with a steel proof mass. When rotator starts rotating, the cantilever will be twisted by the inertial proof mass. Then the corresponding torsional deformation will generate opposite charges in the piezo layer surfaces according to the direct piezoelectric converting effect. Since the charges across the piezoelectric layer surface are electrically separated by the gap in the middle of the electrode, the cancelling effect could be avoided. As the torsional modes





**Figure 1.** Schematic of split-electrode piezoelectric bimorph scavengers

normally happened at the higher working frequencies, this structure could make it possible to work in a wider frequency range by harvesting both bending and torsional mechanical energy.

## 2. Modelling

### 2.1. Modal analysis

In this paper, the presented model is developed in ANSYS13.0. The structure of the split-electrode energy harvesting device is made of substrate layer ( $length \times width \times thickness = 28 \times 9 \times 0.2mm$ ), piezoelectric layer ( $length \times width \times thickness = 20 \times 9 \times 0.1mm$ ) and proof mass ( $length \times width \times thickness = 8 \times 30 \times 1mm$ ) shown as Figure 1. The materials chosen for these three parts are 65Mn steel, PZT-5H and 45 steel. Then density, poisson ratio and Young's modulus of 65Mn steel are  $7850kg/m^3$ , 0.23 and  $198.6GPa$  respectively. And those parameters of 45 steel are  $7850kg/m^3$ , 0.28 and  $205GPa$ . The density of PZT-5H is  $7500kg/m^3$ . The quality factor and dielectric loss are 80, and 0.014. The elasticity stiffness, piezoelectric stress coefficients and dielectric matrix for PZT-5H are shown as following,

$$[C_{ansys}^E] = \begin{bmatrix} 12.6 & 8.41 & 7.95 & 0 & 0 & 0 \\ 8.41 & 11.7 & 8.41 & 0 & 0 & 0 \\ 7.95 & 8.41 & 12.6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.33 \end{bmatrix}, [e_{ansys}] = \begin{bmatrix} 0 & -6.5 & 0 \\ 0 & 23.3 & 0 \\ 0 & -6.5 & 0 \\ 17 & 0 & 0 \\ 0 & 0 & 17 \\ 0 & 0 & 0 \end{bmatrix}, [\epsilon^S] = \begin{bmatrix} 3200 & 0 & 0 \\ 0 & 3200 & 0 \\ 0 & 0 & 3200 \end{bmatrix}.$$

In the analysis, 3-D 20-node coupled-field solid element 226 is used to model the piezoelectric layer, and corresponding structure element is solid 186. As previously illustrated, the steel substrate is sandwiched by two PZT-5H layers, which are set in opposite polarities. The bulk electrode layer is separately modelled using coupled degrees of freedom command. One end of the cantilever is fixed, and the other end is set free. In order to do coupled piezoelectric-circuit analysis, the external load resistance is modelled using resistor option of CIRC94. Then the load resistor is serially connected to the corresponding top and bottom electrodes. The first and second resonant frequencies are calculated to be 105.051 Hz and 252.803 Hz respectively in the modal analysis. As the second resonant frequency is comparable to that of first bending mode, the torsional mode is supposed to be utilised for the environmental vibration energy harvesting. However, In order to prove the efficiency of harvesting energy in torsional mode, both of the bulk-electrode and split-electrode devices are compared in the following analysis.

### 2.2. Optimal load resistance

Since the load resistance is serially connected with top and bottom surfaces of the scavenger, it is necessary to determine the optimal load resistance for maximized harvesting energy according to equation (1),

$$R_{opt} = \frac{1}{\omega_n C_s} \quad (1)$$

Where  $R_{opt}$  is the optimal resistance,  $\omega_n$  is the resonant frequency,  $C_s$  is the serial capacitance which could be obtained by the static analysis in ANSYS software by setting the voltage across the top and bottom surfaces of piezoelectric layer to be 1V. Then the value of capacitance is equal to the value of surface charge. Table 1 is the calculated capacitance and optimal resistances corresponding to each mode.

**Table 1.** Calculated capacitance and optimal resistances corresponding to each mode of the bulk and split-electrode device.

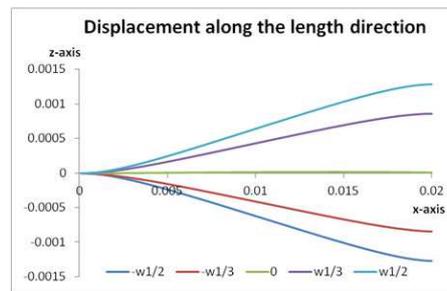
Split 1( $C_1 = 1.963 \times 10^{-8}F$ )		Split 2( $C_2 = 1.963 \times 10^{-8}F$ )		Bulk( $C_b = 3.945 \times 10^{-8}F$ )	
1 <sup>st</sup> mode	2 <sup>nd</sup> mode	1 <sup>st</sup> mode	2 <sup>nd</sup> mode	1 <sup>st</sup> mode	2 <sup>nd</sup> mode
77.176k $\Omega$	32.07k $\Omega$	77.174k $\Omega$	32.069k $\Omega$	38.392k $\Omega$	15.954k $\Omega$

### 2.3. Harmonic analysis

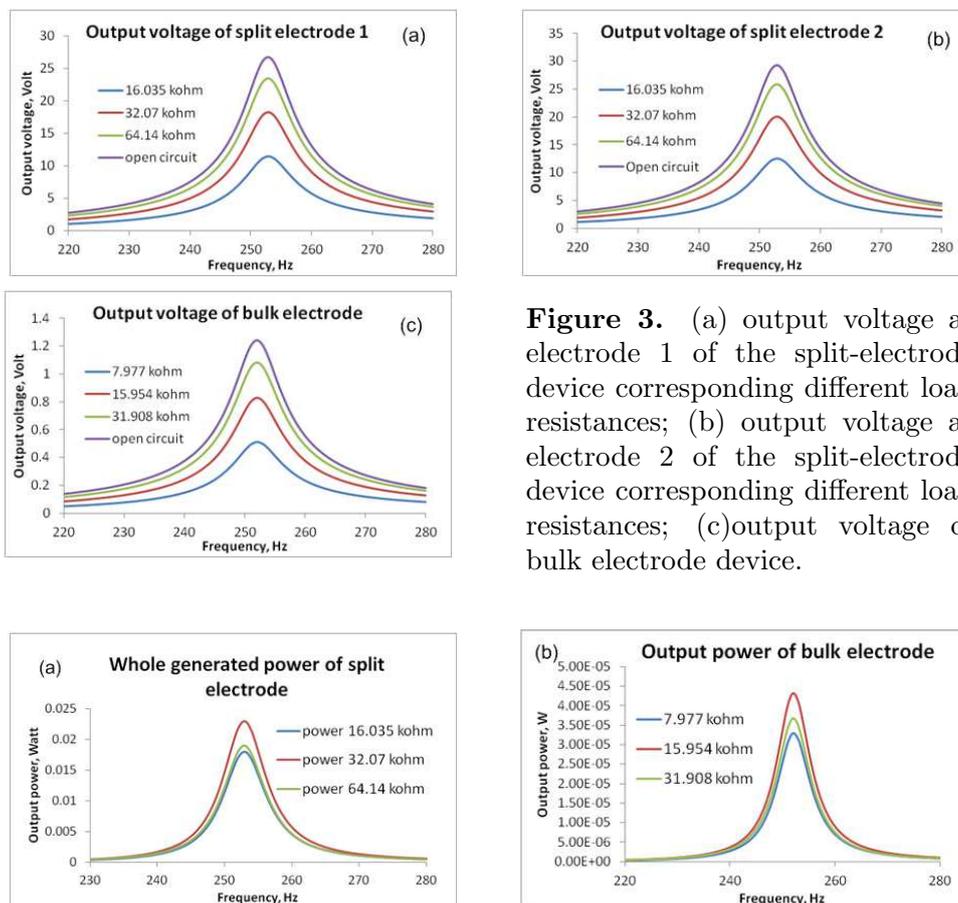
Although the optimal resistance can be theoretically determined by equation (1), it is still necessary to conduct the harmonic analysis with different load resistances to validate the result. The load resistances are set to be 16.035k $\Omega$ , 32.07k $\Omega$ , 64.14k $\Omega$  and open circuit respectively in the split electrode device. For bulk-electrode device, they are set to be 7.977k $\Omega$ , 15.954k $\Omega$ , 31.908k $\Omega$  and open circuit. And the damping ratios of the two devices are both set to be 0.015625. Since the electrode is modeled using coupled degrees of freedom command, it will not change the resonant frequency for the split-electrode device. At the same time, in order to model the torsional mode in harmonic analysis, the proof mass is excited by external forces (with amplitude of 0.16N) along the top surface edges in parallel but opposite directions that shown as Figure 1. Figure 2 is the displacement along the cantilever length at different position in width direction at resonant frequency. It is found in figure 2 that the deformation is symmetric about its central face ( $x, y$  plane in ANSYS software), which results in torsional deformation. And the maximum displacement is shown to be 1.29 mm at the corner points of the free end. Figures 3(a)- 3(c) show the output voltages versus frequencies at torsional mode. The peak voltages for the second mode occur at around 252.503Hz. The output voltages across the load resistor increased with load resistance. Moreover, the output power has optimal values at 32.07K $\Omega$  and 15.954k $\Omega$  for the split and bulk-electrode devices respectively shown in Figures 4(a) and (b), which proves the results calculated by equation (1) to be right. In addition to this, the maximum output voltages and harvested power of split-electrode devices are calculated to be 26.7V, 29.35V and 0.023W, which are much higher than that of bulk one (1.21V and 43.3 $\mu$ W correspondingly), and therefore it demonstrate a clear cancelling effect as reported in reference [5] and [6].

### 2.4. Transient analysis

In real operation, as energy harvesting devices usually work in dynamic vibrations rather than harmonic vibrations, it is necessary to conduct transient analysis to characterise the performance



**Figure 2.** Simulated displacement of the cantilever under torsional loads. Coloured lines represent displacement on cross sectional lines along the length. These cross sectional lines are drawn at different position in width direction.

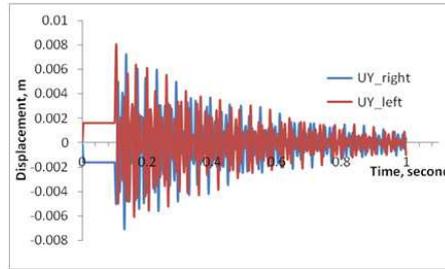


**Figure 3.** (a) output voltage at electrode 1 of the split-electrode device corresponding different load resistances; (b) output voltage at electrode 2 of the split-electrode device corresponding different load resistances; (c) output voltage of bulk electrode device.

**Figure 4.** (a) Whole generated power of split-electrode piezoelectric bimorph scavengers; (b) Output power of bulk-electrode piezoelectric bimorph scavengers.

of energy harvesting devices in a loading cycle. For simplicity, the device is actuated by displacements rather than loading forces in the simulation. The displacement is set to be  $1.6\text{mm}$  equivalent to the loading force ( $0.16\text{N}$ ) in opposite directions at two corners of the surface of piezo layers (shown in Figure 2). And the stiffness matrix multiplier is set to be  $7.87 \times 10^{-6}$ . There are three steps in the loading phases, which are ramp-type loading step with initial displacement

being zero, loading step with constant deformation after phase one and release step followed by structural dynamic vibration. The time is set to be  $0.3ms$  in phase one where the displacement is linearly increased from zero to be  $1.6mm$ , and in phase two the time is set to be  $97ms$  where the displacement being  $1.6mm$  constantly. After phase two, the external load is released and the structure freely vibrates until it reaches stable after  $1s$ . The displacement response at corner points of the top surface of free tip end of the piezo layer in the transient analysis is shown as Figure 5. Since the instantaneous power is calculated by, [2]



**Figure 5.** The displacement at corner of the free end of the cantilever in a transient analysis.

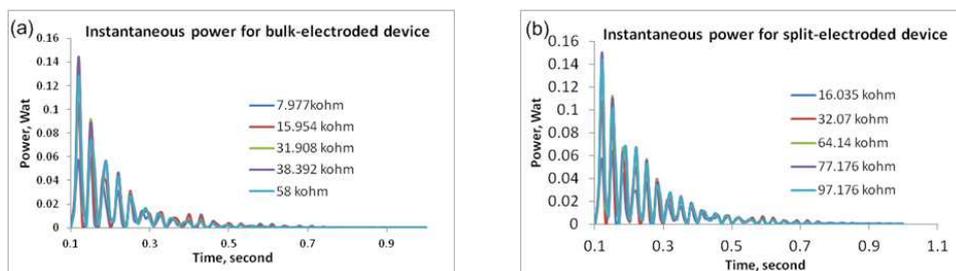
$$P_{(t_i)} = \frac{V^2(t_i)}{R} \quad (2)$$

Where  $V(t_i)$  is the voltage across the resistor at the corresponding sub step, the instantaneous energy and average power are deduced as,

$$E(t_n) = \sum_{i=0}^n P(t_i) \Delta t_i \quad (3)$$

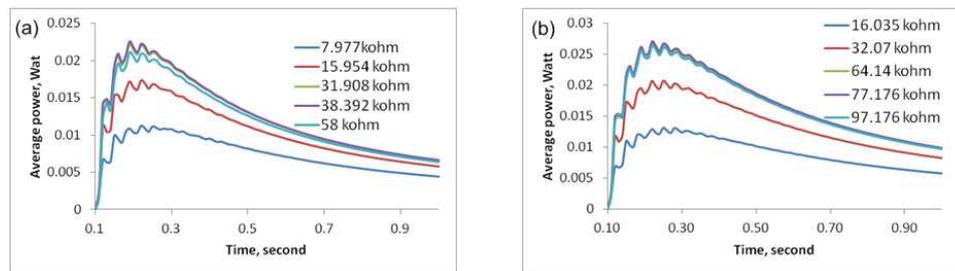
$$P_{av}(t_n) = \frac{1}{t_n} E(t_n) \quad (4)$$

where  $n$  is the number of time step,  $\Delta t_i$  is the duration of every time step,  $t_n$  is the length of time



**Figure 6.** (a) Instantaneous power for bulk-electrode device; (b) Instantaneous power for split-electrode device.

when average power  $P_{av}$  produced. Since the generated energy is much higher in release step than that in loading step, it is only focused on the results in the release step. The instantaneous power for bulk-electrode device and split-electrode device are shown as Figures 6(a) and 6(b), where the ripples of the generated power curves are due to natural vibration modes in the release loading step. In Figure 7, the average power for the two kinds of devices are also presented, where the



**Figure 7.** (a) Average output power of the bulk electrode device in the release step; (b) Average output power of the split-electrode device in the release step.

load resistances are set to be  $7.7977k\Omega$ ,  $15.954k\Omega$ ,  $31.908k\Omega$ ,  $38.392k\Omega$  and  $58k\Omega$  respectively for bulk-electrode device, and split-electrode device being  $16.035k\Omega$ ,  $32.07k\Omega$ ,  $64.14k\Omega$ ,  $77.176k\Omega$  and  $97.176k\Omega$ . It is found that optimal load resistances are  $38.392k\Omega$  and  $77.176k\Omega$  rather than  $15.954k\Omega$  and  $32.07k\Omega$  in the harmonic analysis step. The reason for this phenomenon is because the bending mode is still in a predominant situation in the release step. However, the torsional mode still plays an important role in the whole generated power in the split device, since the maximum average output power of split-electrode device is  $0.0054W$  higher than bulk device, which is almost 25.35% higher than that in bulk electrode device. Furthermore, the maximum output average power occurred at  $0.25s$  and it keeps stable around  $9.85mW$  at  $1s$ . If the loading cycle is repeated, it could make the split-electrode scavenger much more efficient than bulk-electrode device.

### 3. Conclusion

Model of split-electrode piezoelectric bimorph scavengers for harvesting energy from torsional motions has been presented. The torsional modal frequency ( $252.803Hz$ ) is calculated to be comparable with the bending mode ( $105.051Hz$ ) based on the theoretical analysis. It is found that in the torsional mode, the harvested power for the optimal external load resistor ( $32.07Kohm$ ) is  $0.023W$ , which is much higher than that of bulk-electrode device. Moreover, the transient analysis is conducted to characterise performance of the split-electrode device. Harmonic and transient analysis for both split and bulk electrode have been conducted using ANSYS software. The simulation results have shown that the split electrode devices generate much more power bulk electrode devices for any type of vibrational excitations.

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