Design and Analysis of Three DOF Piezoelectric Vibration Energy Harvester

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Abstract: In this research, a MEMS piezoelectric vibration energy harvester with three-DoF (degree-of-freedom) responses is proposed. The device consists of two seismic masses suspended by two sets of T-shape beams and four folded-beams. Piezoelectric films with top and bottom metal electrodes are pre-deposited on the bottom surfaces of the T-shape beams. It utilizes the misalignment of mass centers between the beams and seismic masses to convert in-plane vibration input into out-of-plane rotation of the T-shape beams. The piezoelectric film senses the resulted stress inside the T-shape beams, and generates voltage output to charge batteries or other portable electronics. The vibrational modes of the device are simulated with COMSOL Multiphysics and the resonant frequencies are extracted. The proposed MEMS energy harvester can be attached to shoes, bridges or other vibrating surfaces to harvest energy from movement of walking, running, driving for clean energy generation.

Keywords: Vibration energy harvester, Piezoelectric, Microelectromechanical Systems (MEMS), COMSOL Multiphysics.

1. Introduction

Vibration energy harvester can convert mechanical vibration energy into electrical energy and store it in battery for later use. It can create clean renewable energy from vibration movements such as walking, jumping, running, etc. This can convert energy otherwise wasted into useful energy for charging portable electronic devices. It offers clean and green energy source for future applications. If such vibration energy harvester can be installed in a wide range on roads, bridges, shoes, and other applications, it can recycle a large amount of green energy and help protect the environment. It may also help stabilize the road and bridge surfaces because these energy harvest devices can actually absorb the excessive vibration energy of the surfaces. The energy harvested can be used to charge portable electronics, implanted biomedical devices (e.g pacemakers) so that the battery can last longer before it needs to be recharged. It can also be used for standalone and isolated devices such as wireless sensor network, surveillance video cameras to monitor forest wildfire, so that they can be partially or completed self-powered. MEMS (Microelectromechanical Systems) technology is especially suitable for energy harvester applications due to their small size, low cost and high efficiency. MEMS vibration energy harvesting devices based on electrostatic [1]-[3], electromagnetic [4]-[5], piezoelectric transducers [6-11] have been reported.

In [1], a 3-degree of freedom MEMS energy harvester utilizing electrostatic transducers to convert ultrasonic waves into electrical energy is reported. The device utilizes seismic mass connected to a group of flextures to sense the ultrasonic vibrations. The energy harvested is used to charge a set of in-plane and out-of-plane variable comb storage capacitors. Another MEMS vibration energy harvester using capacitor transducer is reported in [2]. It uses electroplated nickel as structural layer to allow simple post-CMOS modular fabrication. In [3], a SOI-MEMS electrostatic vibration energy harvester for micro power generation is reported. Simulation results show that the device can produce maximum output power of 5.891μW when the excitation frequency is 2 kHz. In [4]-[5], two magnetic MEMS vibrational energy harvesters are reported. Electromagnetic energy harvesters utilize permanent macro magnets to convert energy. Power is generated with the relative movement between the coils and magnetic field, hence no extra operation power is needed. Piezoelectric energy harvesters utilize piezoelectric effect to convert vibration energy to electrical energy. Vibration can induce stress inside the piezoelectric material, this in turn lead to electrical voltage difference between both surfaces of the material, and this voltage can be used to charge batteries. In [6], a MEMS vibration energy harvester using AFM-like piezoelectric cantilevers coupled to a rotating gear is reported. The gear is driven by an oscillating mass. In [7], a MEMS vibration energy harvester using Zinc oxide (ZnO) piezoelectric cantilever for mechanical to electrical transduction is reported. In [8][9], MEMS piezoelectric vibration energy harvester devices with different cantilever structures are simulated for optimized energy conversion efficiency. In [10] and [11], two three-axis piezoelectric vibration energy harvesters which can harvest energy along all X, Y and Z axes were reported. In [10], the seismic mass is connected to four L-shape bulk-PZT/Si beams which can bend along X, Y and Z directions. A set of partitioned electrodes on the PZT arms collect mechanical energy in the transverse piezoelectric mode. In [11], the energy harvester utilizes an out-of-plane proof-mass to induce movement along Z-axis in response to both in-plane and out-of-plane vibrations. The resulted stress due to out-of-plane bending can be harvested by the PZT piezoelectric thin films.

In this paper, a piezoelectric 3-DoF (degree-of-freedom) MEMS vibrational energy harvester is proposed. It has four sets of folded beams and two sets of T-shape beams connected to two seismic masses. The seismic masses are much thicker than the beams, hence the mass center of the seismic masses is out of the beam plane. Piezoelectric films with top/bottom metal electrodes are pre-deposited on the bottom surface of the T-shape beams. If external vibration is along Z direction, the beams bends up and down, hence the induced stress inside T-shape beams can be sensed by the piezoelectric films to generate voltage output. If external vibration is along X or Y direction, the inertial force induces a net torque so that T-shape beam in one end bends up and the T-shape beam in the other end bends down. The stress inside T-shape beams can again be sensed by the piezoelectric films to generate voltage difference between its top and bottom surfaces. Thus the device can harvest vibrational energy along all three degree-of-freedom. The generated voltage is an AC voltage signal. A rectifying circuit is used to convert it into DC voltage to charge portable electronics or a battery, hence the vibration energy is harvested into electrical energy and stored for future usage. COMSOL simulation is used to simulate the vibrational modes of the piezoelectric energy harvester and the corresponding resonant frequencies are extracted. The device can be embedded into shoes, under road surface or attached to human body to convert vibration energy for green energy generation.

2. Vibration Energy Harvester Design

The proposed vibration energy harvester is shown in Figure 1. The device has silicon-on-glass compound structure. The silicon structure and glass substrate are bonded together using silicon-glass anodic bonding. Since we are interested in the vibrational modes of the silicon structure, the glass substrate is not shown in Figure 1.

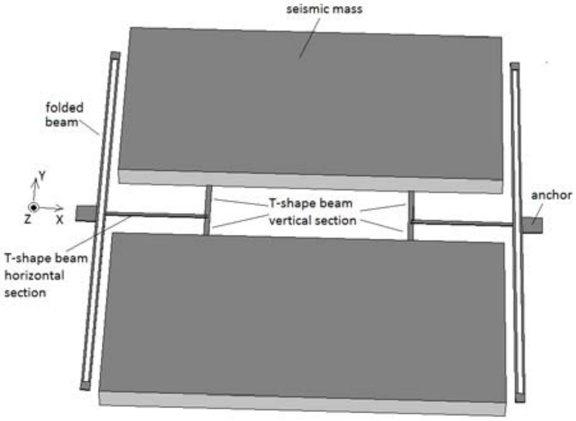

Figure 1: Structure diagram of MEMS vibration energy harvester.

As shown in Figure 1, the device structure consists of two seismic masses suspended by two sets of T-shape beams and four sets of folded beams. One end of the folded beams are fixed to substrate via anchors. Piezoelectric thin films with top/bottom metal electrodes (not shown in the figure) are pre-deposited on the bottom surface of the T-shape beams before silicon-glass bonding. The seismic masses are much thicker than the beams, thus its mass center is above the plane of the beams. This imbalance is intentionally designed to induce out-of-plane movement of both T-shape beams when in-plane vibration is sensed. If there is vibration along X or Y direction within the device plane, the inertial force acting on the seismic masses results in a net torque, which causes one T-shape beam to bend up and the other T-shape beam to bend down, respectively. In addition, if the vibration is along the Z-direction, it causes the T-shape beams to vibrate along Z-direction as well. Thus regardless whether the vibration is in or out of device plane, it results in vibration of the T-shape beams out of the device plane. The piezoelectric films pre-deposited on the bottom surface of the T-shape beams generate voltage difference between its top and bottom surfaces due to the induced stress inside the T-shape beams. The generated voltage passes through a rectifying circuit to charge the battery, so that the vibration energy is harvested and stored as electrical energy for future usage.

For vibration energy harvester, the resonant frequency of the device is a very important parameter. In order to maximize the energy harvesting efficiency, the resonant frequency of the device should be designed to match the frequency range of the vibration to be harvested. For everyday movement such as running and walking, the frequency is generally below 100Hz. The designed energy harvester consists of four folded beams and two T-shape beams. The width, length and thickness of each folded beam section are W_{fb}, L_{fb}, t_b respectively. The width, length and thickness of the horizontal section of the T-shape beam are W_{tb1}, L_{tb1}, t_b respectively. The width, length and thickness of each vertical section of the T-shape beam are W_{tb2}, L_{tb2}, t_b respectively. The width, length and thickness of one seismic mass are W_m, L_m and t_m respectively. Density of silicon is ρ, and Young's modulus of silicon is E. We are going to derive the resonant frequencies of the energy harvester along X, Y and Z directions separately.

For vibration along X direction, both four folded beams and four sections of T-shape beams contribute to it and they are connected in series. The four folded beams are connected in parallel. The total spring constant of four folded beams is

$$K_{fb\_xtot} = 2EW_{fb}^3 \cdot t_b / L_{fb}^3 \qquad (1)$$

Four vertical sections of T-shape beams are connected in parallel. The total spring constant of four vertical sections of T-shape beams is

$$K_{tb2\_xtot} = 4EW_{tb2}^3 \cdot t_b / L_{tb2}^3 \qquad (2)$$

The four folded beams and four vertical sections of T-shape beams are connected in series. The total spring constant of the device along X direction is

$$K_{X\_tot} = \frac{K_{fb\_xtot} \cdot K_{tb2\_xtot}}{K_{fb\_xtot} + K_{tb2\_xtot}} \qquad (3)$$

The total mass of two seismic masses is

$$M = 2\rho W_m L_m t_m \qquad (4)$$

Ignoring the mass of piezoelectric films and its top/bottom electrodes, and treating the energy harvester as simplified spring-mass system, the resonant frequency of the energy harvester along X direction is

$$f_x = \frac{1}{2\pi}\sqrt{\frac{K_{X\_tot}}{M}} \qquad (5)$$

For vibration along Y-direction, only two horizontal sections of T-shape beams contribute to it and they are connected in parallel. The total spring constant of the energy harvester along Y-direction is

$$K_{Y\_tot} = 2EW_{tb1}^3 \cdot t_b / L_{tb1}^3 \qquad (6)$$

The resonant frequency of the energy harvester along Y-direction is

$$f_y = \frac{1}{2\pi}\sqrt{\frac{K_{Y\_tot}}{M}} \qquad (7)$$

For the vibration along Z-direction, all the four folded beams and two T-shape beams contribute to it. The total spring constant of four folded beams along Z direction is

$$K_{fb\_ztot} = 2EW_{fb} \cdot t_b^3 / L_{fb}^3 \qquad (8)$$

The total spring constant of two horizontal sections of T-shape beams along Z direction is

$$K_{tb1\_ztot} = 2EW_{tb1} \cdot t_b^3 / L_{tb1}^3 \qquad (9)$$

The total spring constant of four vertical sections of T-shape beams along Z direction is

$$K_{tb2\_ztot} = 4EW_{tb2} \cdot t_b^3 / L_{tb2}^3 \qquad (10)$$

For vibration along Z-direction, the four folded beams, two horizontal sections of T-shape beams, and four vertical sections of T-shape beams are connected in series. The total spring constant of the energy harvester along Z-direction is

$$K_{Z\_tot} = \frac{1}{(1/K_{fb\_ztot} + 1/K_{tb1\_ztot} + 1/K_{tb2\_ztot})} \qquad (11)$$

The resonant frequencies of the energy harvester along Z-direction is

$$f_z = \frac{1}{2\pi}\sqrt{\frac{K_{Z\_tot}}{M}} \qquad (12)$$

The above equations serve as a rough estimation of the resonant frequencies of the energy harvester along X, Y and Z directions. However, they are based on simplified spring-mass model, which may introduce some errors. In addition, due to the fact the mass center of the beams and the seismic masses are not in the same plane, the device also has rotation/tilting movement in its working mode. The rotation/tilting will be added into the lateral vibrations and change the resonant frequencies. To be more accurate, the actual resonant frequencies of the energy harvester should be simulated with COMSOL FEM (Finite Element Method) simulation.

3. Use of COMSOL Multiphysics

COMSOL Multiphysics is used to simulate the top 6 vibration modes of the designed vibration energy harvester. During COMSOL simulation, we used Solid Mechanics module and Eigenfrequency study was performed on the device. We also observed how vibrations along X, Y and Z directions cause the T-shape beams to vibrate/rotate along Z directions. This out-of-plane vibration/rotation of the T-shape beams induces stress inside the beams, and it is sensed by the piezoelectric films on the bottom surface of the beams to generate voltage output. This is how the energy harvester convert mechanical vibration energy into electric energy.

The design parameters of the piezoelectric energy harvester device is listed in Table 1.

Table 1. Design parameters of the energy harvester

Components	Design parameters
Folded beams (4 sections)	Beam width W_{fb}=40µm Beam length L_{fb}=4000µm Beam thickness $_{tb}$=20µm
Horizontal sections of T-shape beams (2 sections)	Beam width W_{tb1}=2000µm Beam length L_{tb1}=80µm Beam thickness t_b=20µm
Vertical sections of T-shape beams (4 sections)	Beam width W_{tb2}=100µm Beam length L_{tb2}=900µm Beam thickness t_{b2}=20µm
Seismic masses (2 masses)	Mass width W_m=7600µm Mass length L_m=4000µm Mass thickness t_m=400µm

The material used for vibration energy harvester device structure is single-crystalline silicon. The material selected from the built-in material library in COMSOL, and all the mechanical and electrical properties are already pre-defined. Since we are interested in finding the vibrational modes and resonant frequencies of the silicon structure, the piezoelectric thin film is not included in the model. Different piezoelectric materials give different output voltages for the same stress input. PZT-5H material can be a good choice for the piezoelectric film. The meshed model of the energy harvester is shown in Figure 2.

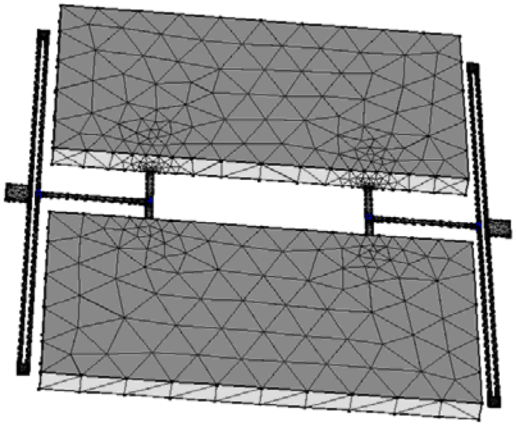

Figure 2: COMSOL meshed model of the MEMS vibration energy harvester

4. COMSOL Simulation Results and Discussion

The piezoelectric vibration energy harvester device is designed and simulated in COMSOL. Modal simulation is performed on the device to extract its first six vibrational modes and corresponding resonant frequencies. The vibrational modes and the corresponding resonant frequencies are shown as below.

The first vibrational mode is show in Figure 3, with the resonant frequency of f_1=15.57514Hz. As we can see, this is the mode in response to vibration along Y direction. Since the mass center of seismic masses is not in the same plane as that of the beams, the inertial force induces a net torque so that the seismic masses tilt around the X axis. This causes the T-shape beams to tilt and the resulted stress inside the T-shape beams lead to voltage output of the piezoelectric films.

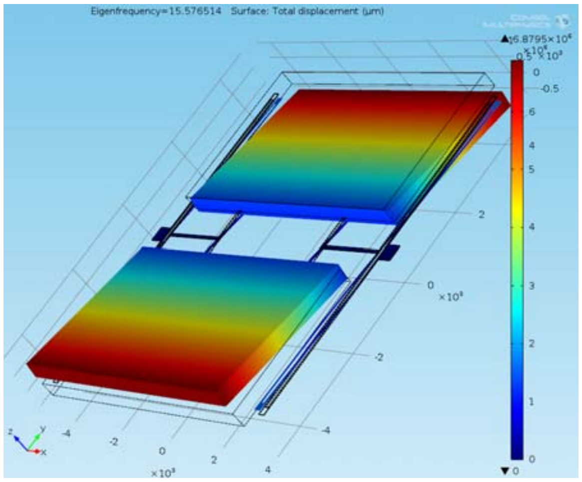

Figure 3: First vibration mode: for vibration along Y-direction (resonant frequency f_y = 15.57514Hz)

COMSOL simulation result of the second vibration mode of the energy harvester is show in Figure 4, and the corresponding resonant frequency is f_2=21.473948Hz. This is the vibration mode in response to input vibration along Z direction. Both seismic masses move up and down along Z direction in this mode. As a result, both the folded beams and both sections of T-shape beams bend up and down, resulting out-of-plane movement of the beams. This in turn causes stress inside the beams, and leads to the voltage output of the piezoelectric films on the bottom surface of the T-shape beams.

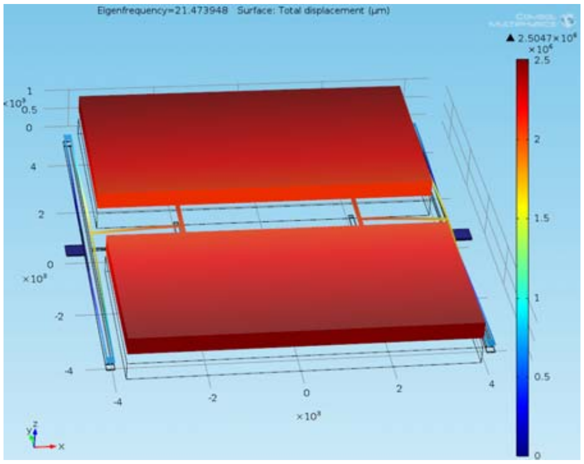

Figure 4: Second vibration mode: for vibration along Z-direction (resonant frequency $f_z = 21.473948$Hz)

COMSOL simulation result of the third vibration mode of the energy harvester is show in Figure 5, and the corresponding resonant frequency is f_3=41.367501Hz. This is the vibration mode in response to input vibration along X direction. The inertial force experienced by the seismic masses induces a net torque and cause the seismic masses to rotate. The left and right portions of the seismic masses tilt up and down around Y direction. Thus one T-shape beam bends up and the other T-shape beam bends down. The out-of-plane bending causes T-shape beams to induce internal stress, which causes the piezoelectric films to generate voltage output between its top and bottom surfaces.

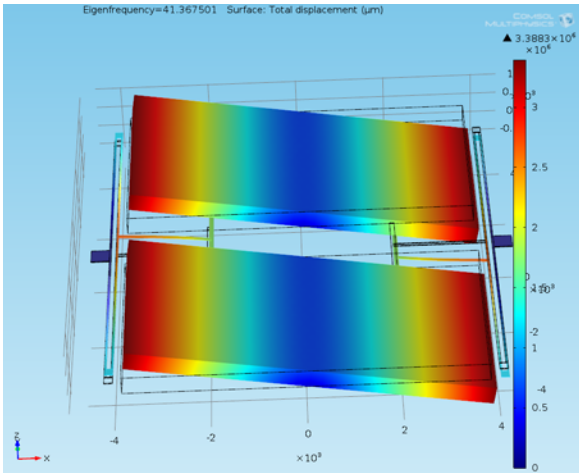

Figure 5: Third vibration mode: for vibration along X-direction (resonant frequency $f_x = 41.367501$Hz)

The COMSOL simulation results for the higher vibrational modes are also obtained. However, they lead to higher order vibrations of energy harvester including the twisting of multiple beams and the masses. As a result, they are not the working modes of the energy harvester and they are not listed here.

Based on the COMSOL simulation, we can see that for vibrations along X, Y and Z directions, they all lead to out-of-plane vibration of the T-shape beams. This will induce internal stress inside the beam material, which cause the piezoelectric films on its bottom surface to generate voltage output. The AC voltage output will pass through a rectifier circuit to be converted into DC voltage so that it can be used to charge portable electronic devices or batteries. In this way, the vibration energy from the surrounding environment can be harvested and stored for future usage. Since it can harvest vibration energy from all three DoFs (degree-of-freedoms), it is more effective than the energy harvesters which are sensitive only along one direction. The resonant frequencies of the first three vibrational modes are all less than 50Hz, which are good match for the typical frequencies of everyday movement. One possible application of the device is to harvest energy from human activities such as walking, jumping or exercising. Due to MEMS technology, the device size can be very small and it can be easily embedded inside the sole of shoes, as shown in Figure 6. When people walk, run or do exercise, the energy of the vibration of the shoes can be harvested and stored in rechargeable battery for future usage. The energy harvester device can be used to charge the battery of backup battery of smart phones, digital camera or other portable electronics. This creates "green" energy and offers a convenient way for people to recharge their cellphone batteries "on-the-run". People walk, run and do exercise every day. If all the shoes are embedded with such MEMS energy harvester, it can result in tremendous amount of clean energy. This can help protect the environment and it is truly a "green" technology.

Figure 6: Shoe with vibration energy harvester inserted in its sole

5. Conclusions and Future Work

In this paper, a MEMS energy harvester which can harvest energy along all three DoFs (Degree-of-freedoms) has been studied. The energy harvester uses inertial sensing technique to sense the input vibration and convert it into electrical energy to be stored for future applications. The device has different thickness for its beams and the seismic masses. Due to this imbalance, the inertial force resulted from input vibration leads to a net torque and converts in-plane vibration into out-of-plane movement of the T-shape beams. The input vibration along Z axis will result in the bending of T-shape beams along Z direction as well. The piezoelectric films on the bottom surface of the T-shape beams sense the stress inside the T-shape beams and generate voltage output. The generated AC voltage passes through a rectifier circuit to be converted into DC voltage to charge portable electronic devices or batteries. Compared to energy harvester sensitive to one direction, the proposed device results in more energy harvesting along all directions. COMSOL Multiphysics is used to simulate its vibrational modes and the corresponding resonant frequencies were extracted. From the COMSOL simulation results, the working vibration modes in X and Y and Z directions have resonant frequencies of f_x=41.367501Hz, f_y=15.57514Hz and f_z= 21.473948Hz respectively. Due to its small size, it is especially suitable to be embedded inside the sole of shoes, tires, road surface, bridges or other places with frequent vibrations. It can harvest energy from vibrations where such energy was traditionally wasted.

In the future, we will perform stress simulation to find out the maximum stress induced inside the T-shape beams due to input vibrations along X, Y and Z directions. We will also perform piezoelectric simulation to find out the actual voltage output due to input vibrations.

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