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Design optimization in geometry of seismic mass for MEMS based cantilever type piezoelectric energy harvester for motor vibrations

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Piezoelectric energy harvesters are suitable for vibration energy harvesting due to simple design, operation and fabrication in MEMS technology. Cantilever structures fixed from one end and seismic mass at the other must tune to different resonance frequency to ensure wideband frequency operation. Adequate width to length ratio of cantilever is required to avoid curling of cantilevers (bending). Effect of increase in width of the cantilever structure on resonance frequency has been investigated and also compared analytically in this paper. An optimized design has been proposed which compensates for the increase in resonance frequency due to increase in width by changing the geometry of the seismic mass. With the change in geometry of seismic mass a shift in center of mass has been achieved towards the free end of the cantilever which reduces the resonance frequency which is desirable. The design optimization of seismic mass reported in this paper reduces the resonance frequency by 4.27 % which is appreciated as it is required to harvest ambient vibrations having low frequency.

Keywords: Microelectromechanical system (MEMS), Micromechanical resonators, Piezoelectric energy harvester, Energy harvesting, Motor vibrations

1 Introduction

Recent advancements in microelectronics, miniaturization of devices have reduced the power required for device operation to micro and nano-watt levels[1]. Meanwhile, wireless sensor networks are gaining importance day by day because of their small size, low-power consumption, and ability to operate in remote places[2]. They are widely used in various applications such as environmental monitoring, structural health monitoring, etc. Considering the small size and remote use of these devices, one major challenge is the energy source[3]. One way is to use traditional batteries which are difficult to replace once exhausted and are also bulky which affects the size of the device, and another way is to harvest energy from the environment such as ambient heat, light, radio signals, and vibrations[4]. Vibrations of varying amplitudes and frequencies are freely available in the environment and power of up to hundreds of microwatts can be generated[5]. This makes them suitable to drive the wireless sensor nodes therefore vibration energy harvesting is suitable for wireless sensor networks, for motor vehicle vibrations, human body vibrations, etc[6]. Most vibration-based micro-electromechanical system (MEMS) energy harvesters are based on electromagnetic, capacitive, and piezoelectric transduction mechanisms[7, 8].

Out of the three, the piezoelectric type is the best choice because of the simplicity of device operation and using variations in structure parameters (i.e., length, width, and thickness) and material properties, so that this type can adapt to a wide range of ambient frequencies[9]. Piezoelectric energy harvesters can operate efficiently if the system frequency resonates with the frequency of the ambient vibration, otherwise the output of the device would drastically reduce[10]. Length of the cantilever is varied to provide frequency adaptability as length is having inverse non-linear relation with frequency[11]. Cantilever array of elements having variable length is designed to achieve wideband frequency operation but as length increases curling (bending) of cantilevers affects the operation[12]. Each cantilever resonates with ambient vibration and generates output, whereas other cantilevers generate residual output adding to the net potential generated. Therefore array of cantilevers act as a band pass filter system[13]. Width of the cantilever

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is also an important parameter as it gives strength to the beam and also sufficient area to deposit piezoelectric material on top[14]. Width to length ratio must be maintained to avoid curling of cantilevers but increasing the width increases resonance frequency of the cantilevers[15]. Shape of the seismic mass also has a significant impact on the output potential generated[16]. Different shapes such as square shape, pyramidal shape and triangular shape have been investigated in the past[17]. The electrode area has also an impact on the resonance frequency of the energy harvester[18]. Therefore, due to increase in the width and the thickness of the electrodes resonance frequency of the energy harvester increases. As ambient vibrations are of low frequency the energy harvester device must resonate at low frequency[19]. Hence, the energy harvester device should be designed in such a way that it should have lower resonance frequency. In this paper, the increase in the resonance frequency due to increase in the width of the cantilever is compensated by shifting the center of mass of the seismic mass. The proposed design can also be used to harvest energy for motor vibrations. The optimized design suggested with reference to length, width, thickness and placement of seismic mass helps in the fabrication of a prototype which also avoids curling of cantilever beam. It can be fixed on the chases of wheel to harvest motor vibrations.

2 Design and Simulation of Cantilever Type Piezoelectric Energy Harvester

In this section cantilever based piezoelectric energy harvester is designed and simulation of the design is performed, analyzed and compared. External vibrations displace cantilever (fixed from one end and free from other end with seismic mass) producing stress on the fixed end resulting in generation of potential. Frequency of the cantilever depends on spring constant (k) and seismic mass (*m*) at the free end as described[2] by Eq. (1):

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad \dots (1)$$

$$k = \frac{EWt^3}{4l^3} \qquad \dots (2)$$

Cantilever with seismic mass is modeled by spring mass damper systems having a fixed resonance frequency. Seismic mass reduces the resonance frequency of the system which is required to tune with ambient vibrations of low frequency. Ambient frequency vibrations range from few Hz to around 2 kHz therefore the length of the cantilever and seismic mass can be adjusted to resonate with the ambient vibrations. Increasing the length of the cantilever is preferred as it reduces the resonance frequency non -linearly given by Eqs (1) and (2). As discussed the cantilever structure should resonate with ambient vibrations of low frequency, for this length of the cantilevers beams are increased. Typical range for length of the beams ranges from 2200 µm to 2000 µm which gives resonance frequency[11] from 681 Hz to 1215 Hz. Wideband frequency operation is achieved by using array of cantilevers having different length, as the length increased curling of cantilevers affects the operation of the device. Curling affects the dominant mode operation of the cantilevers (±Z direction) by exciting secondary modes affecting device operation. Width to length ratio must be maintained to avoid curling, but as width is increased resonance frequency of the cantilever also increases. This increase in the frequency due to increase in width should be compensated for successful device operation. In the next section center of mass of seismic mass is shifted to compensate the effect of increase in width on resonance frequency of the cantilever.

2.1 Optimization of seismic mass to compensate effect of width on resonance frequency of the cantilever

Width of the cantilever is an important parameter because as length is increased curling (bending of cantilevers) of cantilevers takes place which affects the operation of the device in the dominant mode [3]. Width to length ratio for the device needs to be optimized in order to avoid curling effect. Therefore in this section effect of width on the resonance frequency of the cantilever is analytically calculated[9] using Eq. (3) and compared with finite element method (FEM) simulation for three cases listed in Table 1.

An optimized design is obtained by adjusting the center of mass of the seismic mass so as to compensate the increase in resonance frequency due to the increase in width of the cantilever. The volume of the seismic mass is kept constant for all three cases.

$$f = \frac{1}{2\pi}\sqrt{\frac{YWh^3(r^2+6r+2)}{12\, m\, l^3(8r^4+14r^3+10.5r^2+4r+\frac{2}{3})}} \qquad \dots (3)$$

Where W and h are width and thickness of cantilever, Y is Young's modulus, m is weight of seismic mass, l is length of cantilever without proof mass, x is distance of center of mass of seismic mass from cantilever, r = x/l.

Case 1: Young's modulus of polysilicon *(Y)* is 169 GPa, width of the cantilever *(W)* is 100 µm, thickness of cantilever beam *(t)* is 2 µm, weight of seismic mass *(m)* is 0.0020952×10^{-6} kg having dimensions as length = 400 µm width = 100 µm thickness = 22.5µm giving center of mass at (200, 50, 11.25), so the effective cantilever length without seismic mass *(l)* becomes 1200 µm. Ratio r is defined as center of mass in x direction to the effective length of the cantilever beam as shown in Fig.1(b), i.e., 0.166 for case 1. The resonance frequency calculated analytically using Eq. (3) is equal to 375 Hz. FEM simulation using Comsol multiphysics is also carried out for the aforesaid dimensions of the cantilever single beam giving resonance frequency at 353 Hz which is shown in Fig. 2.

In case 2 the width of the cantilever is increased to 150 µm and seismic mass dimensions are defined as length 400 µm width 150 µm thickness 15 µm having center of mass at (200, 75, 7.5). Ratio r is same 0.166 as in case 1 which gives resonance frequency at 460 Hz when calculated analytically using Eq. (3). FEM simulation for the case 2 design is carried out which gives resonance frequency as 421 Hz as shown in Fig. 3. It can be observed that there is rise in the resonance frequency due to increase in the width of the cantilever which is also justified by Eq. 2.

Now to compensate for this increase in resonance frequency due to increase in width of the cantilever an optimized design is proposed by changing the geometry of the proof mass and discussed as case 3.

Table 1 — Case study

	Total length of cantilever (µm)	Width (µm)	Seismic mass (μm^3)
Case 1	1600	100	9×10^5
Case 2	1600	150	9×10^5
Case 3	1600	150	9×10^5

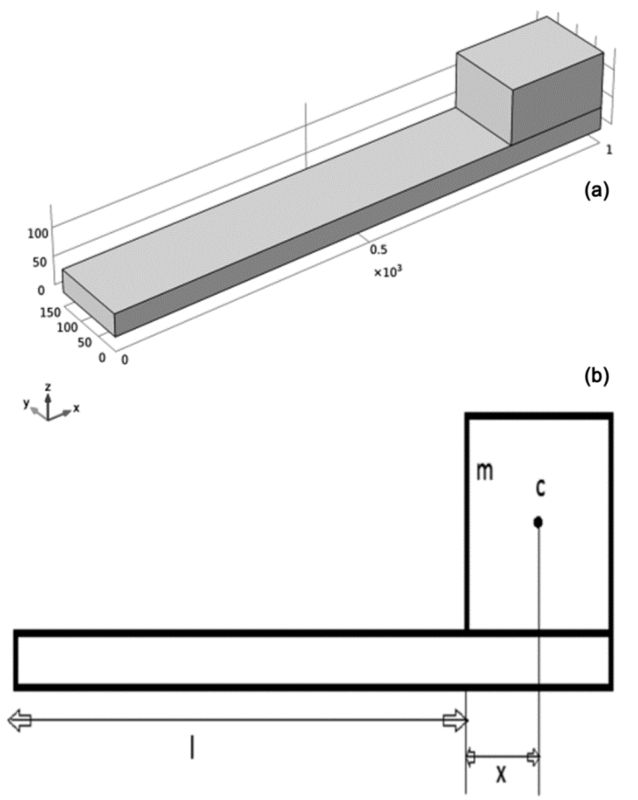

Fig. 1 – (a) 3D Schematic of cantilever with proof mass and (b) 2D Schematic showing labeled dimensions of cantilever structure with proof mass.

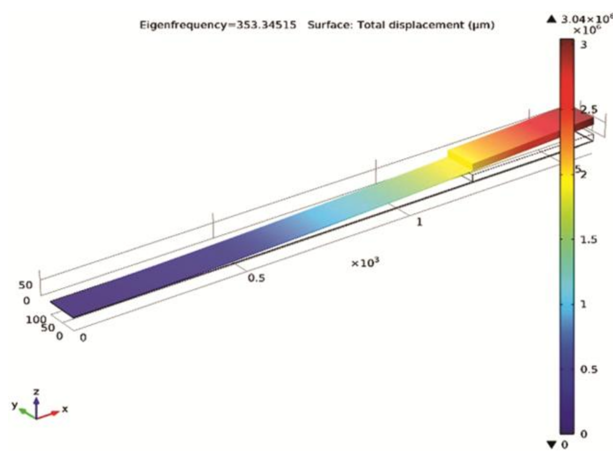

Fig. 2 – Snap shot of resonance frequency of the cantilever having width 100 µm for case 1 is 353 Hz.

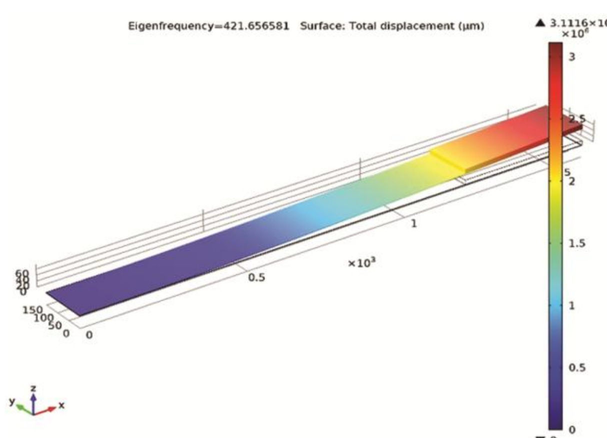

Fig. 3 – Snap shot of resonance frequency of the cantilever having width 150 µm for case 2 is 421 Hz.

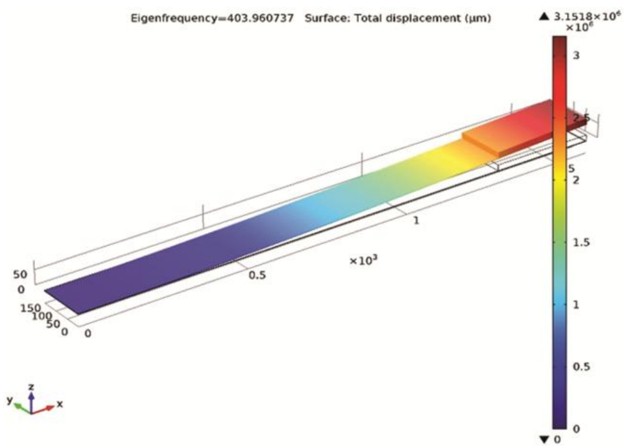

Fig. 4 – Snap shot of resonance frequency of the cantilever having width 150 µm for case 3 is 403 Hz.

Width of the cantilever is 150 µm, seismic mass dimensions are length 300 µm width 150 µm thickness 20 µm with center of mass at (150, 75, 10), effective cantilever length is 1300 µm giving r as 0.23. Again resonance frequency calculated using Eq. (3) for case 3 is equal to 371 Hz. When FEM simulation is done for case 3 gives it resonance frequency as 403 Hz shown in Fig. 4. It can also be seen that for the three cases the resonance frequency calculated analytically and using FEM are in close agreement with each other. Thus from all the three cases, it can be depicted that when the width of the cantilever is increased whereas center of mass remained same as in case 1 it resulted in increase in resonance frequency. Whereas when the dimension in case 3 of the seismic mass is adjusted so that its center of mass gets shifted towards right side or free end of the cantilever the resonance frequency decreases. Center of mass for third case gets shifted by 50 µm in x-direction towards right side which reduces the resonance frequency of the cantilever to 403 Hz which results in reduction of resonance frequency by 4.27%. Therefore for reduction in resonance frequency and to avoid the curling of cantilever beam case 3 is appropriate.

3 Conclusions

Increase in width of the cantilever increases the resonance frequency, an optimized design is obtained by changing the geometry of the seismic mass which shifts the center of mass towards the free end of the cantilever which compensates for the increase in the resonance frequency due to increase in width of the cantilever. Width of the cantilever is adjusted from 100 µm to 150 µm which results in increase in the resonance frequency from 353 Hz to 421 Hz. Center of mass of the seismic mass is varied from (200, 75, 7.5) to (150, 75, 10) by changing the geometry of seismic mass, i.e., 50 µm in x-direction towards the free end of the cantilever which results in reduction of resonance frequency by 4.27% at 403 Hz. Therefore for reduction in resonance frequency and to avoid the curling of cantilever beam case 3 is appropriate for designing cantilever type piezoelectric energy harvester. The proposed design can also be used to harvest energy for motor vibrations. The prototype can be fabricated and fixed at the chases of the wheel to harvest the motor vibrations

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