Research Paper

Numerical Investigations of a Novel Sliding Support Cantilever Design for Vibration Energy Transduction

R. Rathishchandra Gatti
Mechanical Engineering Dept., Sahyadri College of Engineering & Management, Adyar, Mangalore-575007
Email: rathishchandra.mech@sahyadri.edu.in

Abstract

Cantilever topologies are very commonly used in energy transduction mechanisms which involved cyclic dynamic loads such as frequency tachometers for detecting the vibration frequency or energy harvesters for generating energy from wasted vibrations. Another advantage of the cantilever topology is its scalability to MEMS level compared to other spring structures such as helical and leaf springs etc. The natural frequency of the cantilever depends on its length and this factor is utilized here to envisage a novel topology for construction of energy transducers. A numerical investigation using nite element analysis is initially done to understand the variation of the natural frequency with respect to the changing length for a single cantilever beam. This is cross validated using analytical results.

Keywords: Cantilever, broadband, energy transduction, varying length, electromagnetic, piezoelectric, power harvesting, energy harvester, micro-electromechanical systems, biosensors, sensors.

1 Introduction

Recent advances in energy harvesting transducers and vibration sensors have necessitated the scientists to try for di erent topological approaches to transduce vibration energy into electrical energy [1]. Cantilever beam structures are commonly used in converting vibration energy to usable electrical energy such as those found in piezoelectric vibration energy harvesters [2] and sensors such as Micro-electromechanical systems (MEMS)biosensors [3]. One of the key interests of the vibration energy harvesting research is the ability of the energy harvesters to generate power for a range of frequencies for which several topologies have been investigated and reported. A few techniques include frequency up-conversion [4], spatially varying the magnetic eld [5], using non-linear oscillators [6] to name a few. This key design requirement of broadband energy harvesting is addressed in the proposed design.

In the proposed design, a lumped mass single degree of freedom spring mass damper system is proposed where the spring is a cantilever xed at one end and the lumped mass suspended on the free end. The novelty in the proposed design is a sliding support or base that varies the overhanging length of the cantilever thus leading to the desired natural frequency. The inspiration for the proposed design is the design of Fullerton tachometer wherein the length of the suspended cantilever is adjusted by a screw in between the xed structure and the free end with lumped mass. Another inspiration for the proposed design are the promising results of the feasibility of creating sliding contacts in MEMS as discussed by Ingrid Ku [7]. One important tribological design constraint is to minimize the frictional wear while designing sliding MEMS contacts since the surface friction coe cient is high due to high surface to volume ratio in MEMS structures. This can be minimised to acceptable levels of $\mu = 0.05$ to 0.1 for less than 100rpm by using low viscosity lubricants such as Octadecylamine 0.1% in Silicon oil [7].

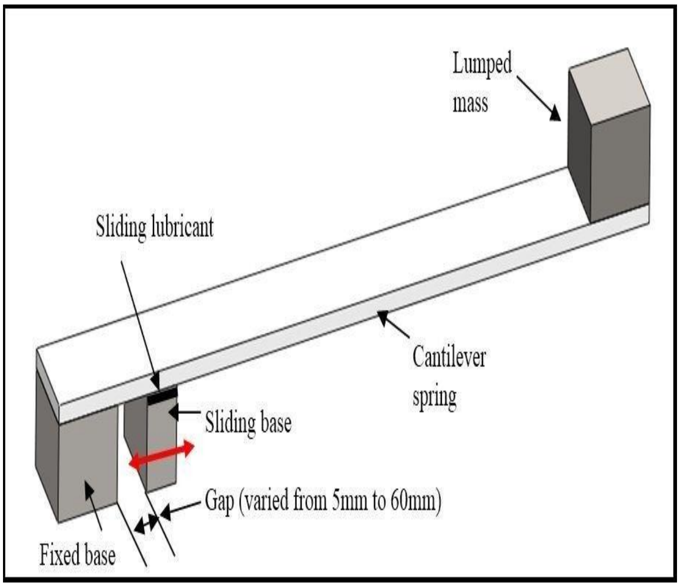

Figure 1: Sliding support cantilever design.

Since the sliding speed does not exceed as high as linear equivalent of 1000 rpm where $\mu > 0.2$, it is assumed that sliding MEMS contacts are feasible to go ahead with the proposed design.

2 Design

The sliding support cantilever design is as shown in the Figure 1. It consists of a cantilever spring made of a exible material. The spring is supported on two supports - a xed base and a sliding base. A lumped mass is suspended on the free end of the cantilever spring.

The natural frequency of the cantilever with free ends is given by,

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{ml^3}} \quad (1)$$

where E = modulus of elasticity of the cantilever beam, I = mass moment of inertia, m = mass of the lumped mass suspended, l = overhanging length of the cantilever beam. In the proposed design, the length l can be varied by increasing the gap between the xed base and the sliding base.

Commonly available materials such as PET for cantilever spring, plain carbon steel for xed and moving support were considered for the proposed mesoscopic design (at mm scale). At MEMS scale the choice of materials will de nitely shift towards thin lm polyamides and other exible substrates for cantilevers and Silicon for lumped mass, xed support and moving supports for the ease of fabrication. However, the scope of this study is limited to understand the dynamic behaviour and modal frequency response of this unique design rather than identi cation of the material selections for the MEMS fabrication which can be considered in the future work and therefore not in scope of this study. The main interest of designing any vibration energy harvester design is its ability to harvest energy over the range of frequencies from random vibrations. Hence, linear dynamic FEA analysis with random base excitation load was performed to understand and know the modal frequencies of the cantilever at di erent varying lengths. In the FEA simulation, the gap between the xed support and the moving support was varied from 5mm to 60 mm in steps of 5mm.

3 Simulation

3.1 Simulation Setup

Linear dynamic FEA analysis using random vibration was performed to understand and know the modal frequencies of the cantilever at di erent varying lengths. In the FEA simulation, the gap between the xed support and the moving support was varied from 5mm to 60 mm in steps of 5mm at lab temperature of 25°C.

3.2 Linear dynamic analysis simulation conditions

The entire assembly was meshed using a solid mesh using 8550 tetrahedral elements with element size of 1.652 mm and 14169 nodes as shown in Figure 2. The xed base and the sliding base was xed using the xed geometry conditions. A practical average value of 2mm amplitude was considered for the base excitation load condition that was applied on the bottom surfaces of the xed base and the sliding base. The iterative solver namely the FFEPlus solver in Solid works was used rather than the accurate direct sparse solver due to insu cient memory space and longer time required by direct sparse solver.

4 Results and Discussion

The energy transduction of the energy transducer depends on its amplitude of vibration. Also, the energy conversion is maximum when the prominent frequencies of the source of vibration are in resonance with the natural frequency of the energy transducer. The proposed design considers varying cantilever length and hence the modal frequencies of the energy transducer will also need to be observed. Hence, the post processing of the simulation results was done to obtain the stress, displacement and the modal frequencies from the linear dynamic FEA simulation.

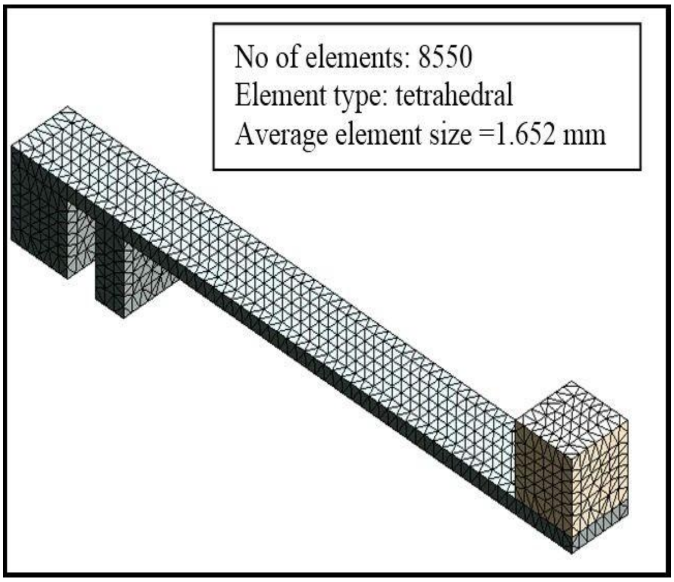

Figure 2: Finite element Mesh using Solid mesh.

4.1 Stress and Displacement results

For the design to be safe, the distortion energy theory and hence, the Von-Mises stress analysis was considered. As seen in Figure 3, the Von-Mises stress was found to be maximum at 0.0377N/m^2 and was within the limits of yield point of the cantilever spring. This was because the base displacement of 2mm was too low for inducing any high stresses at the stress zones. It was also because of the high yield strength of Plain carbon steel that was chosen for the cantilever spring.

As evident in Figure 4, the displacement of the tip of the mass was maximum. The maximum displacement of the cantilever beam is found to vary from 1.23 mm for 60mm gap to 5.76 mm for 5mm gap. The mass tip excitation to the base excitation magni cation ratio was thus 1.23/2 = 0.615 for 60mm gap and 5.76/2 = 2.88 for 5 mm gap. This is true since the length of the overhang of the cantilever decreases with the increase of gap. The top down approach of the energy harvester design would be to estimate the amplitude of vibration required and then design the sliding base energy harvester to appropriate range of length variations.

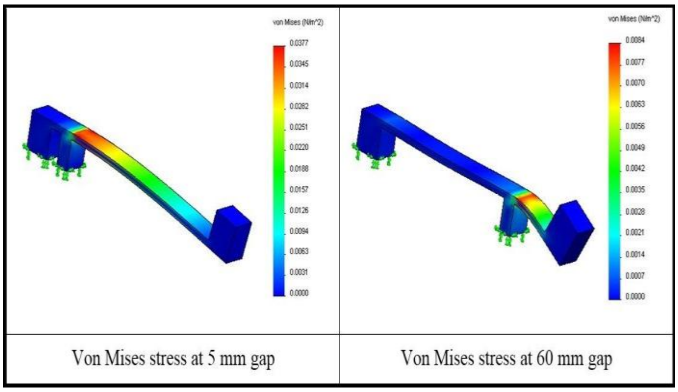

Figure 3: Von-Mises stresses shown for 2 extreme positions of sliding base.

4.2 Random vibrations modal analysis

Most of the energy harvesters based on seismic masses are designed to operate at their fundamental modes but the knowledge of higher modes is bene cial to understand the structural failure modes. The natural frequencies at the fundamental modes (fundamental natural frequencies) and the second modes is shown in the Figure 5. It can be seen that as the gap between the supports increases, the overhanging length decreases thus increasing the natural frequency which inversely depends on the overhang length. It can also be deduced from Figure 5 that one can design an energy harvester for a particular frequency range and then set the minimum and maximum limits of the gap variation between the supports in this harvester design.

As observed in Figure 6, the higher mode natural frequencies tend to vary non-linearly with the increase in gap between the supports. At mode 5, the modal natural frequencies increase up to 35 mm and then decreases which is due to buckling and the mode shapes of vibration. However, most of the practically available industrial vibrations with higher amplitudes fall within 1000 Hz and thus this will not seriously a ect the energy harvester design.

4.3 Application of the proposed design

The proposed design can be used for designing piezoelectric, electrostatic, and electromagnetic or a combination of two or more of these transduction technologies. It can readily be applied to piezoelectric based energy harvesters. One concept design of a MEMS piezoelectric energy harvester is as shown in the Figure 7 below. This concept consists of a xed base and a sliding base with low viscosity lubricants such as Octadecylamine 0.1% in Silicon oil [7] being provided between the sliding contact surfaces. The cantilever can be made of a polyamide with piezoelectric ally active properties such as PVDF-TrFE [8]. The lumped mass can be made of a high density material or the same material as that of cantilever depending on the ease of fabrication.

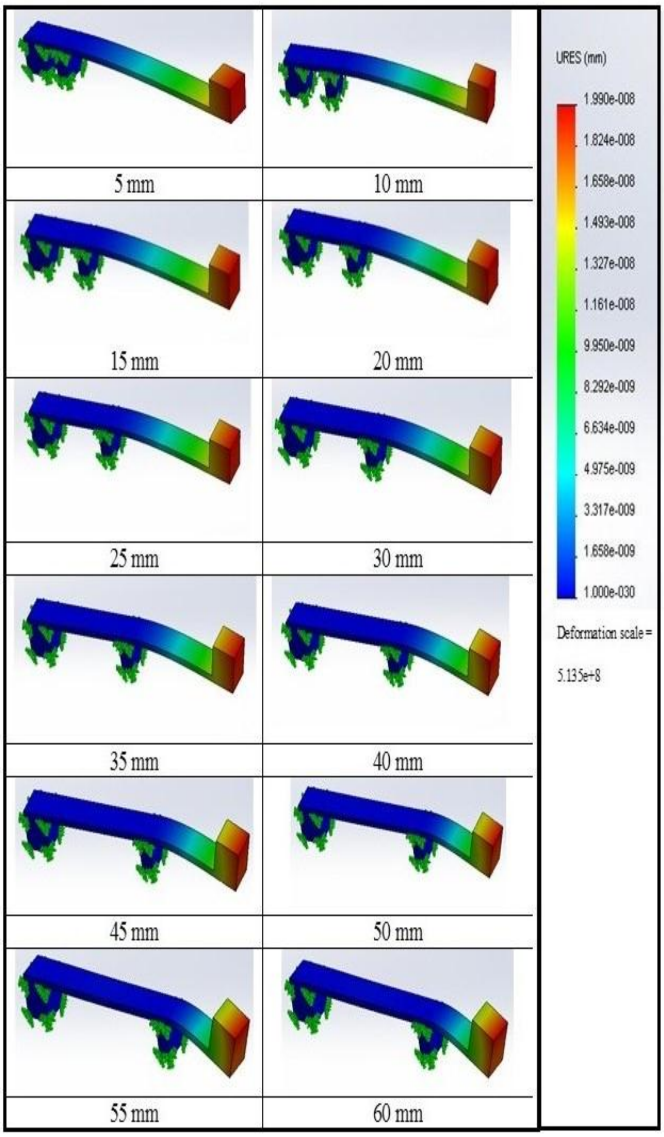

Figure 4: Displacements shown for 2 extreme positions of sliding base.

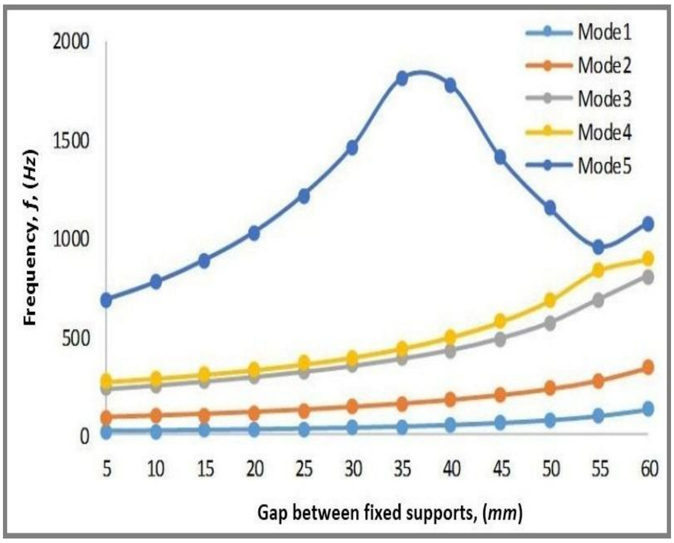

Figure 5: Modal frequencies of the sliding base cantilever at fundamental mode and higher modes.

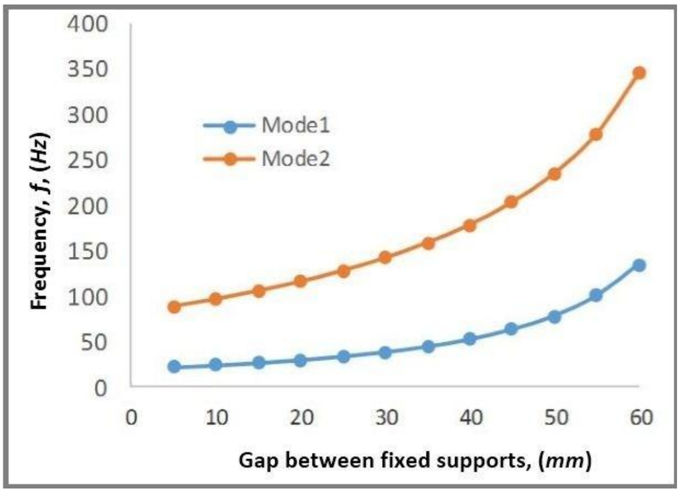

Figure 6: Modal frequencies of the sliding base cantilever at fundamental mode and secondary modes.

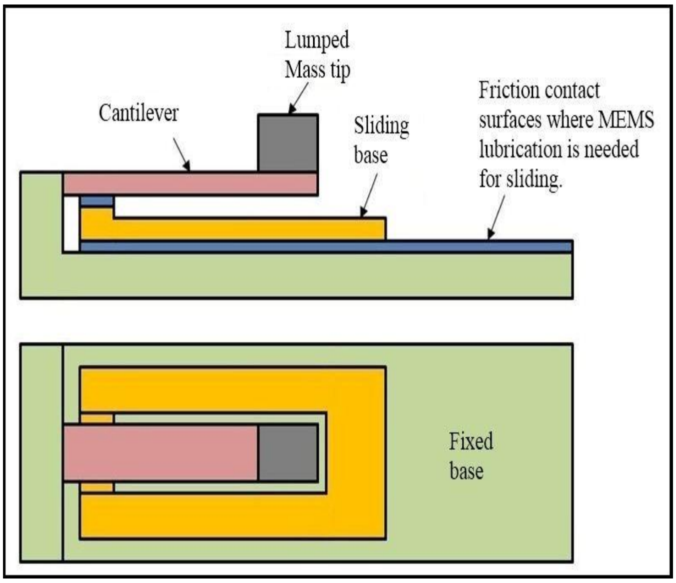

Figure 7: Concept design of a MEMS piezoelectric energy harvester.

5 Conclusion

A novel cantilever energy harvester design is proposed that consists of a xed base and a sliding base to vary the length of the cantilever. A linear dynamic FEA analysis for random vibrations is simulated with a base excitation of 2 mm. The length of the gap is varied from 5mm to 60 mm to observe the change in natural frequency, maximum Von-Mises stress levels and maximum displacements. It was observed that an energy harvester can adopt this design to harness a range of frequencies by changing its length using the sliding contact. The future challenge is MEMS fabrication and study of tribological design considerations to reduce friction.

Acknowledgement

The author would like to thank Professor Ian M. Howard, Department of Mechanical Engineering, Curtin University, Australia for providing his in-depth knowledge and guidance in vibration energy harvesting research during the author's PhD work, which has fuelled the author's work even today.

References

[1]S. Priya and D.J. Inman, eds. "Energy harvesting technologies", New York-Springer, pp. 2-4, 2009.

[2]M. Lumentut and I. M. Howard, "Electromechanical nite element modelling for dynamic analysis of a cantilevered piezoelectric energy harvester with tip mass o set under base excitations", Smart Materials and Structures, vol. 23, pp. 095037-095061, 2014.

[3]A. Porwal, et al., "Microcantilever based biosensors", IETE Technical Review, vol. 19, pp. 257-267, 2002.

[4]M. A. Halim, H.O. Cho and J.Y. Park, "A handy motion driven, frequency up-converting piezoelectric energy harvester using exible base for wearable sensors applications", IEEE SENSORS, pp. 1-4, 2015.

[5]R. R. Gatti, "Spatially varying multi degree of freedom electromagnetic energy harvesting", PhD Thesis, Curtin University, Australia, 2013.

[6]D. A. Barton, S.G. Burrow and L.R. Clare, "Energy harvesting from vibrations with a nonlinear oscillator", J. Vibration and Acoustics, vol. 132, pp. 021009- 021016, 2010.

[7]I. Ku, "Lubrication of High sliding machines", PhD Thesis, Imperial College, London, 2010.

[8]K. R. Rashmi, S. Rai, R. R. Gatti, A. Jayarama, N. Bappalige, N. Joshi, R. Pinto and S. P. Duttagupta, "Simulation and fabrication considerations of P(VDF-TrFE) cantilevers", Sahyadri International Journal of Research, vol. 1, pp. 8-10, 2015.