Design and Simulation of MEMS Based Piezoelectric Vibration Energy Harvesting System

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Abstract: This paper discusses the simulation studies on a vibration based energy harvesting system to convert the undesirable mechanical vibration to useful green power. The design consists of a resonating proof mass and a spring system enclosed in housing and fixed on the source of vibration. A piezoelectric suspension acts as the transducer and generates a voltage that is used to charge the batteries of the portable device after suitable signal conditioning. An array of such piezoelectric generators can be used for improved bandwidth response. The device dimensions are in the millimeter range and can be attachedwith an adhesive to the source of vibration. The device is designed and analyzed by simulation in COMSOL Multiphysics 4.2a to arrive at an optimal geometry and tuned parameter for maximum efficiency of conversion.

Keywords: Energy Harvesting, Vibration, COMSOL, Piezoelectric Transduction.

1. Introduction

The need for energy harvesting from the surroundings is becoming more and more critical as devices become smaller, independent of the electric grid and mobile. Periodic recharging of the batteries depending on the drainage is not possible in most of the wireless networks as this requires proximity to the electric outlets. Also the disposal of the battery after its usable life time is a major problem for the environment. Due to all these reasons along with the search for cleaner and greener forms of energy, attention has focused on the development of converting existing renewable and waste energy into useful energy for devices. The most common sources of such energy are the solar radiation, thermal differentials, vibration and RF emissions [1].The power from an industrial vibration source can be of the order of 100μW/cm^2 [1] and is sufficient for carefully designed ultra-low power devices.

In this paper we discuss the use of a resonating proof mass to harvest energy from machine vibrations.

1.1 Vibration based energy harvesting

The vibration energy harvesterconsists of a proof masssuspended by support legs to the housing. When the housing is accelerated by a mechanical vibration,the mass moves relative to the housing and this available energy is extracted by themicro-generator. The proof mass, springs and damper control the amplitude and frequency of the oscillations. The device is designed in such a way that the proof mass natural frequency matches with the vibration frequency of the source. This ensures that there is a resonance or maximum amplitude oscillation of the proof mass and hence maximum coupling from the source to the transducing mechanism.

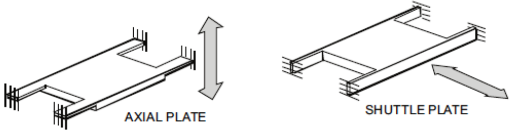

Figure 1: Principal proof mass and suspension geometries for inertialenergy harvesters- axial plate and shuttle plate [1]

The first step in the development of a vibration energy harvesting systemis to identify and select a source of vibration that gives a constant vibration at a fixed frequency for example, machinery in industries. The proof mass spring system is then tuned to the frequency of vibrations. A software model is developed for simulation and optimization studies carried out. The transducer mechanism is tested for generating maximum output and the design of a converter and/or storage circuit is completed. Redesign may be necessary in order to accommodate the variations from the simulated model and the realresults obtained by a prototype.

2. Theory and Principle

There are three possible types of devices in order to convert vibration energy into electrical energy: electrostatic, electromagneticand piezoelectric. Electromagnetic transducers are most commonly used at the macro scale and mostly with the pin shuttle geometry but their integration in the micro scale is challenging due to the design of coils and micro scale magnets. Electrostatic devices operate by moving the plates of the capacitor against each other by a mechanical force. This device can work over a range of input motions, but the capacitor has to be charged initially with a battery for measuring the displacement. Hence this is not an ideal mechanism for energy harvesting. Piezoelectric devices produce output effectively even atlow frequencies, and generally at reasonably high voltage levels [1].

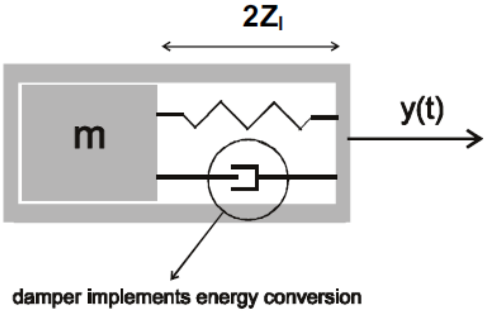

Figure 2: Schematic of linear inertial energy harvester. A springsuspension supports a proof mass m within a frame, motion of the mass onits spring is excited by motion of the host structure y(t), and damping of thisinternal motion by the transducer generates electrical power[1].

The power levels theoretically achievable from inertialharvesters with linear proof massmotion are limitedby four parameters: the proof mass and range of internaltravel of the device, m and $2Z_l$, and the amplitude andfrequency of the source motion, Y_o and ω (assuming harmonic source motion). The theoretical maximum forthe harvested power is found from literature [1] to be:

$$P_{max} = 2m\omega^3 Y_o Z_l / \pi \text{ [Watts]}$$

The power generated decreases with dimensions and with the vibration frequency. For human motion based harvesting, the frequencies are of the order of a few cycles/s, and hence the power density is poor. An optimized value of volume and hence the mass, has to be arrived at depending on the energy demands of application.

3. Use of COMSOL Multiphysics

The vibration energy harvesting system was modeled and simulated using COMSOL Multiphysics 4.2a –piezoelectric devices module.

Materials: Theproof mass and suspension was made of PZT-5H material. The material properties inbuilt into the software were used for the simulation. We also performed a comparative study of three most common piezoelectric materials- ZnO, $BaTiO_3$ and PVDF for the proof mass to optimize for maximum output voltage.

Geometry: The proof mass is designed to be square prism of side length 2500 μm, and of variable height for tuning the device. The suspension is spider leg geometry with fixed constraints at one end and fixed to the proof mass at the other.

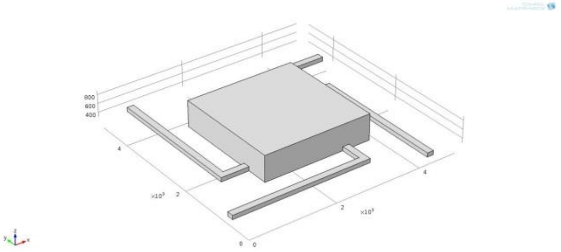

Figure 3: Proposed Geometry of vibration energy harvester

Module used and study type: The piezoelectric device physics module was used to simulate the device. The microgenerator is first tuned to 1 kHz, by varying the height of the proof mass and the suspension. For this, the eigen frequency response was calculated. The force (representative of the acceleration felt in the device) is applied at the top face and the side face of the proof mass to simulate the axial plate and shuttle plate geometry.

5. Equations

The theoretical maximum forthe harvested power is found from literature [1] to be:

$$P_{max} = 2m\omega^3 Y_o Z_l / \pi \text{ [Watts]}$$

6. Results and discussions

The simulation result for the vibration energy harvesting system is obtained as shown:

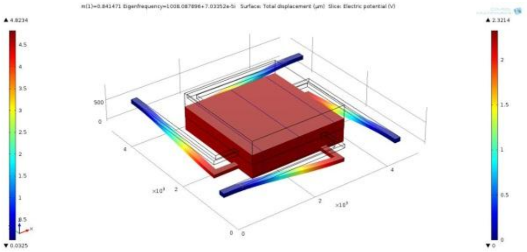

Figure: Device in axial mode

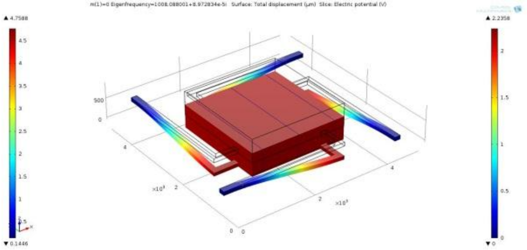

Figure: Device in shuttle mode

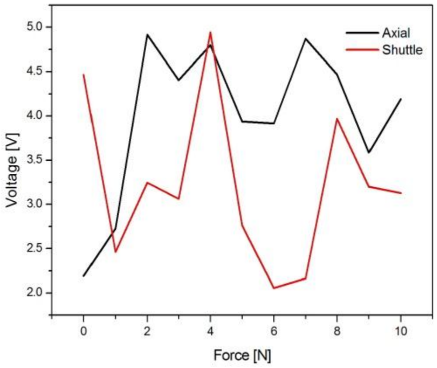

Figure: Comparison of output voltages of axial plate and shuttle plate devices

The change in natural frequencies for different piezoelectric materials used for the same geometry is tabulated below. The maximum rangeof travel of the proof mass and the electric potential varies with the material.

Material (density in kg/m^3)	Eigen frequency (kHz)	Displacement (µm)	Electric potential (V)
PZT (7500)	1.008	2.1896	3.4372
BaTiO$_3$ (5700)	1.434	0.1002	1.9866
ZnO (5680)	1.552	0.2667	4.521

Table 1: Output obtained from different piezoelectric materials

7. Future work

The main limitation of this device is that the output energy generated is very less if the source frequency is different from the resonant frequency of the proof mass [3]. The bandwidth response can be improved with an array of generators tuned to slightly varying frequencies. Electrical tuning of the output circuit is also a feasible option [3] and needs to be addressed in our future work. The electrical equivalent model for the piezoelectric device has a capacitance at the output impedance. By load matching with a variable resistor or resistor-inductor combination at the signal conditioning end, the device can show a wider frequency response.

7. Conclusion

The mathematical model of a MEMS based piezoelectric vibration energy harvesting device was designed and the Finite Element Analysis simulation completed.

The device is designed to resonate at 1 KHz to match the source vibration. The proof mass displacement and the voltage generated for various frequency vibrations are determined and plotted. A maximum voltage of 4.9V is generated for the applied force of 1.8N, which is common when the vehicle encounters a hump on the road.

Further, we found that the axial plate geometry results in a more uniform voltage value for changing loads as compared to the shuttle plate geometry for energy conversion. The effect of different piezoelectric materials is also studied. It is proposed that by using an array of such devices tuned to slightly different frequencies, a wide bandwidth response can be obtained. Further work is required to fabricate and integrate the system for real world application.

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