Simulation of a High Compliant Micro Electromagnetic Generator for Energy Harvesting

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ABSTRACT

This paper describes modeling and simulation of a micro electromagnetic generator for vibration energy harvesting. High compliant diaphragms, including cantilever and spiral, are characterized by using CoventorWare^{TM} on the vibration frequency and amplitude. Simulation results show that a spiral diaphragm has higher compliance and lower resonant frequency than a cantilever diaphragm. The generator with proof mass on this diaphragm has larger vibration amplitude, and it generates higher power output at a lower frequency. The compact generator occupies a volume of 10×5.5×1 mm^3, and is compatible with MEMS fabrication techniques. Based on the Faraday's law of induction, the spiral diaphragm with proof mass provides large rate of change of the magnetic flux. The generator can generate electromotive force at a vibration frequency of 13.95 Hz and amplitude of 1306.88 μm under 1g acceleration with high energy conversion efficiency.

Keywords: MEMS, energy harvest, electromagnetic generator

1 INTRODUCTION

Nowadays, various alternative energy or green energy, such as wind power, solar energy [1], and vibration energy [2], has been widely investigated to overcome the energy shortage. Energy harvester, which acquires energy from the environment, has become a promising substitutive power source. By integrating with microelectromechanical systems (MEMS) technology [3], the device can be small enough to provide power to implantable medical or consumer electronic applications.

When a generator experiences vibration motion, three kinds of transconduction mechanisms in MEMS technology are commonly used: vibration energy can be converted into electric power through electrostatic, piezoelectric, or electromagnetic operation. The electromagnetic method has higher energy conversion efficiency than piezoelectric method, but with much more complicated fabrication processes [4].

The proposed generators are designed to have large displacements at low fundamental resonant frequency with small device volume. By utilizing translational or rotational vibration energy from environmental (or human) activities, the generator can act as a substitutive power source for consumer electronics and carried-on medical equipment.

2 DESIGN AND SIMULATION

Figure 1 shows the basic principal for a typical micro electromagnetic generator, which is composed of a fixed magnet, a copper coil, and a diaphragm where the coil locates (with or without proof mass). As the copper coil moves up and down due to external vibration, magnetic flux changes and electrical power generates at the terminals of the coils.

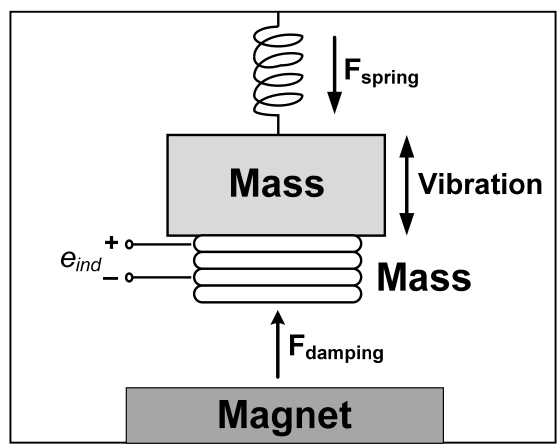


Figure 1: Principal of a micro electromagnetic generator. [5]

To scavenge vibration frequencies from environment, the generator is designed to have a resonant frequency less than 100 Hz with a heavy proof mass. Compliant diaphragm is used to supports the multi-turn coil and proof mass. The diaphragm and proof mass is made of 50 μm and 500 μm thick silicon, respectively. The copper coil is 100 μm wide and 50 μm thick.

The generated power is analyzed according to the Faraday's law of induction: induced electromotive force (emf) is proportional to the rate of change of the magnetic flux. The governing differential equation for a mass–spring–damper system can be written as:

$$\ddot{y} + 2\zeta\omega_n\dot{y} + \omega_n{}^2 y = F(t) \quad (1)$$

, where $\zeta = c/2\omega_n m$ and $\omega_n = (k/m)^{½}$, y is the displacement of the system, F is the external force.

The frequency response (displacement of the mass relative to the external force) can be derived by taking Laplace transform of the equation 1. The magnitude of the frequency response can be written as:

$$|H(\omega)| = \left|\frac{Y(\omega)}{F(\omega)}\right| = \frac{1}{k}\frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}}$$

, where k is the stiffness constant of the system, ω is the operation frequency.

From the Faraday's law of induction, the emf induced in a coil of N loops can be shown as:

$$e = -N\frac{d}{dt}\int_S \vec{B}\cdot d\vec{S} \quad (3)$$

, where S is a surface bounded by the coil loop.

Since the magnetic flux change rate is proportional to the displacement, the amount of power generated by a micro generator from a vibrating surface can be evaluated by means of the amount of displacement.

3 SIMULATION

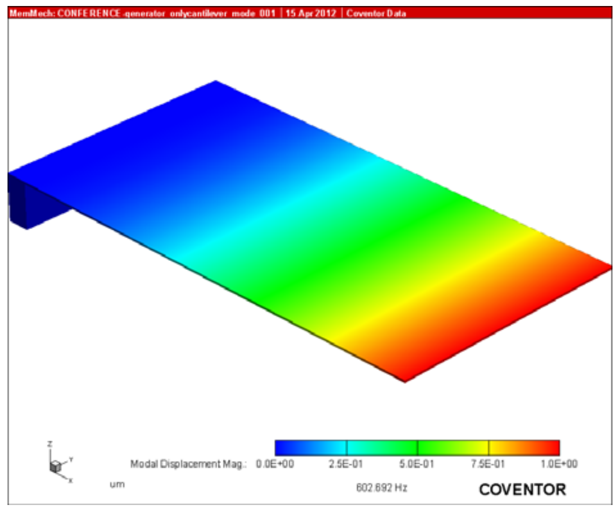
The mechanical finite element analysis is performed using CoventorWare^{TM}. This prototyping electromagnetic generator converts change of magnetic flux to induced electromotive force (EMF) from environmental vibration energy. The simulated resonant frequency and displacement are listed in the following paragraphs.

High compliant diaphragms, including cantilever and spiral, are investigated for stress and displacement under 1g (=9.8m/s^2) acceleration. Table 1 shows the simulated results of the cantilever and spiral diaphragm. For the cantilever, the maximum mises stress is 0.13 MPa and the maximum displacement is 1.056 μm. For the spiral, the maximum mises stress is 3.2 MPa and the maximum displacement is 165.5 μm. Therefore, the spiral diaphragm has higher compliance and larger magnetic flux change rate under fixed vibration energy.

To design generators for large displacements at low fundamental resonant frequency, proof mass is further taken into consideration. Figure 2 shows the simulated results of a cantilever with or without adding proof mass at its free end. The fundamental resonant frequency drops to 221.34 Hz from 602.692 Hz after adding proof mass on the cantilever. In addition, simulated resonant frequency of a spiral coil with or without proof mass at its center are showed to be 13.95 Hz and 40.90 Hz.

Diaphragm	Maximum Mises Stress (Mpa)	Maximum Displacement (μm)
Cantilever	0.13	1.056
Spiral	3.2	165.5

Table 1: Simulated stress and displacement of cantilever and spiral diaphragm under 1g acceleration



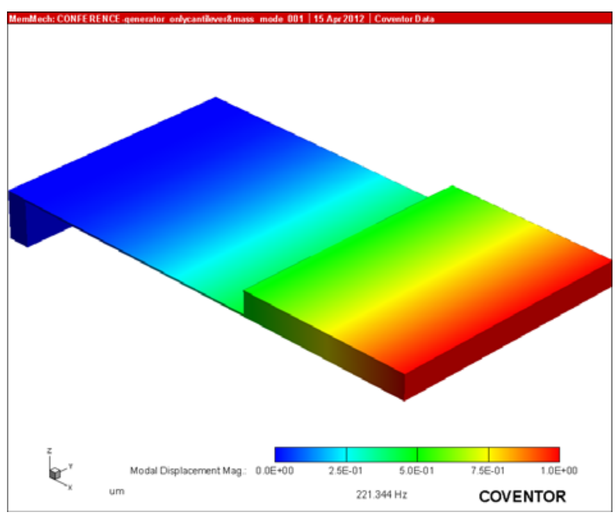


Figure 2: Simulated resonant frequency of (Top) a cantilever (602.692 Hz); (Bottom) a cantilever with proof mass at its free end (221.34 Hz).

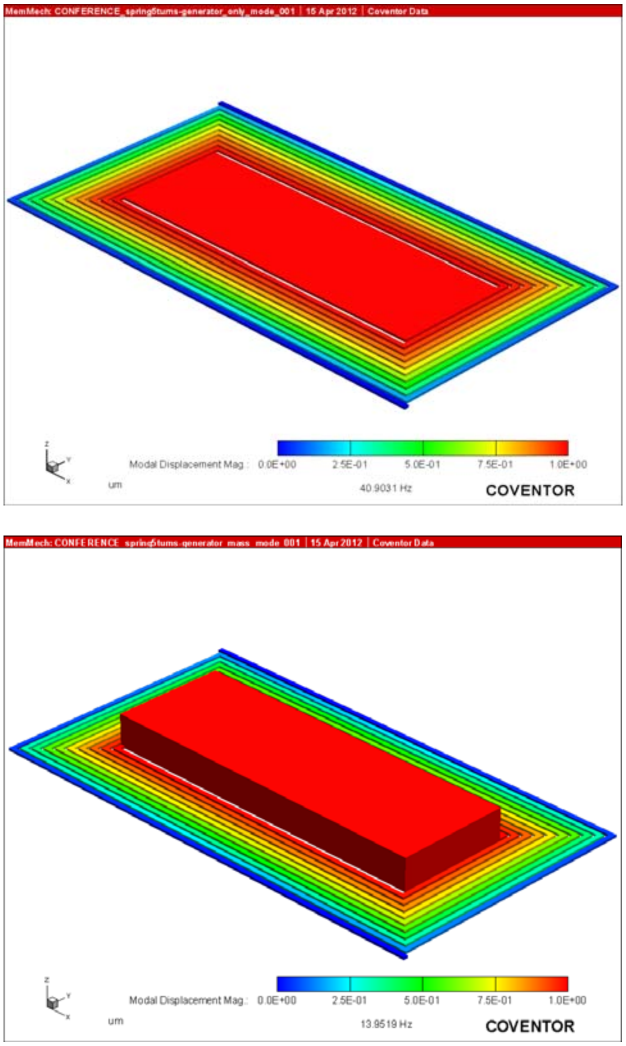


Figure 3: Simulated resonant frequency of (Top) a spiral coil (40.90 Hz); (Bottom) a spiral coil with proof mass at its center (13.95 Hz).

Type	**Resonant frequency (Hz)**	**Maximum displacement (μm)**
Cantilever	602.692	1.056
Cantilever with proof mass	221.34	6.7
Spiral diaphragm	40.90	165.5
Spiral diaphragm with proof mass	13.95	1306.88

Table 2: Simulated resonant frequencies for various types of diaphragms with/without proof mass.

Table 2 summarizes the simulated fundamental resonant frequencies and maximum displacements under 1g (=9.8m/s^2) acceleration with respect to two kinds of diaphragms with or without proof mass, which shows the addition of proof mass efficiently increases the displacement and decreases the fundamental resonant frequency.

4 CONCLUSION

Through this simulation technique, a prototyping micro generator for higher energy conversion efficiency can be designed. The generated power is analyzed according to the Faraday's law of induction, which makes it a practical solution in conserving energy from all kinds of vibration sources. Therefore, a high efficient energy harvester with small mechanical structures can be potentially integrating with CMOS circuits and real-time recharge the devices.

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