DESIGN AND OPTIMIZATION OF AN ELECTROMAGNETIC MICRO ENERGY SCAVENGER WITH PARYLENE CANTILEVERS

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Abstract: This paper presents the design, optimization, and implementation of an electromagnetic micro energy scavenger that uses an array of parylene cantilevers on which planar coils are fabricated. The coils are connected electrically in series to increase the voltage that is generated by virtue of the relative motion between the coils and the magnet. A detailed mathematical modeling and optimization of the design for various cases are carried out. The mathematical modeling is also verified by continuous modeling approach and finite element analysis. The designed generator is fabricated in micro scale and tested for performance. Initials tests show that the micro energy scavenger can generate a maximum voltage of 3.6 mV at a vibration frequency of 4.156 kHz.

Key Words: Micro power generation, energy scavenging, energy harvesting, electromagnetic.

1. INTRODUCTION

With the recent improvements in the micro-system technology, many of the sensor systems and other electronic equipments used in our daily life are now smaller and require less power to operate. Following these improvements, supplying power to these devices became an attracting research area. In this new research area, the main aim is to find ways to self-power these devices by the already available environmental energy sources, including solar, thermal, and vibrations. These are clean and vast energy sources and it is possible to scavenge enough energy to power micro devices. Among these alternatives, vibration is particularly attractive due to its richness in nature. So far in the literature, several vibration based scavengers such as electromagnetic, electrostatic, and piezoelectric have been proposed.

In this paper, a vibration based electromagnetic micro energy scavenger that consists of an array of parylene cantilevers has been proposed. The proposed generator is first designed by a detailed mathematical model and then optimized using a Pattern Search Algorithm. Afterwards, the generator is fabricated in micro scale and tested for performance. In the foregoing sections, modeling, optimization, and fabrication of the generator together with the test results are presented.

2. DESIGN AND MODELING

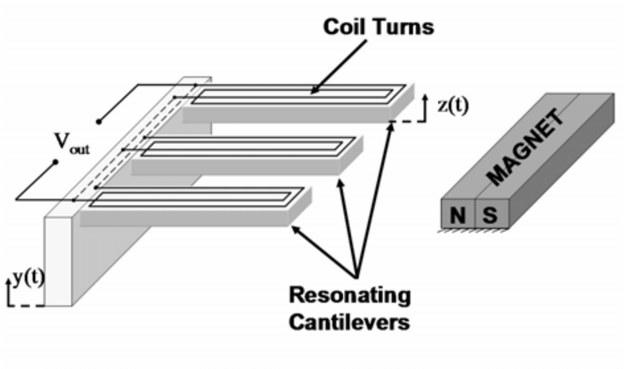

Fig. 1: Schematic view of the proposed generator.

Figure 1 shows the proposed design, which consists of coils fabricated on cantilevers that are capable of moving with respect to a stationary magnet. The macro scale version of a single cantilever made of glass is previously tested by Mizuno et. al [1]. In our design, an array of cantilevers is fabricated and tested in micro scale. Besides, it is shown that, by following a suitable design procedure reasonable output levels can be obtained even from a micro scale implementation. Another important point in this work is that the array of cantilever design is further improved by introducing Parylene C material as the structural element for cantilevers. It allows much larger deflections before mechanic failure compared to silicon [2] and also it can easily be deposited and patterned by standard micro fabrication steps.

As the first step of the design procedure, a mathematical model of the dynamic motion of the cantilevers is constructed. Based on this model, the generated voltage is defined in terms of system parameters. After obtaining necessary equations, the cantilever parameters are optimized using a Pattern Search Algorithm in Matlab to obtain maximum output from the generator. As the final step of the design procedure, the optimized parameters of the cantilevers is checked against mechanical failure using the stress equations developed for the cantilevers.

As explained above, first of all a suitable mathematical model for the cantilever dynamics is constructed. This can be done by an equivalent 2nd order mechanical model such as the one shown in Figure 3.

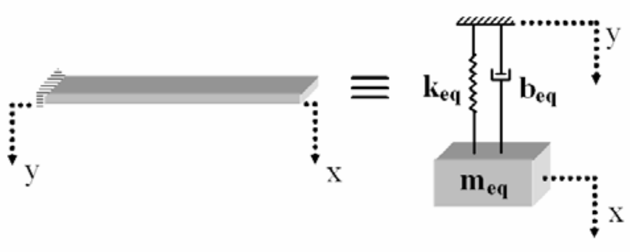

Fig. 3. Equivalent 2nd order mechanical model.

The differential equation of motion for the model is determined by Newton's 2nd Law as,

$$m_{eq}\ddot{z} + b_{eq}\dot{z} + k_{eq}z = -m_{eq}\ddot{y} \tag{1}$$

In this equation, m_{eq}, k_{eq}, and b_{eq} are the equivalent mass, stiffness, and damping, respectively. z is the relative displacement of the cantilever tip with respect to its fixed end and y is the base displacement of the support. Using the model given above, the natural frequency of the first bending mode is determined from,

$$\omega_n = \sqrt{\frac{k_{eq}}{m_{eq}}} = 3.57\sqrt{\frac{EI}{mL^3}} \tag{2}$$

where E, I, m, and L are modulus of elasticity, area moment of inertia, mass and length of the cantilever, respectively. The equivalent mass and stiffness terms are also two important design parameters used in the optimization, which are defined by $k_{eq} = \frac{3EI}{L^3}$ and $m_{eq} = \frac{33}{140}m$ [3].

After obtaining the mechanical model for the system, a suitable electrical model for the coils should be derived. This can be done by using Faraday's Law of Induction and the induced voltage on the coils is defined by,

$$\varepsilon = -\frac{d\Phi}{dt} = -\frac{d\left(\int \vec{B}\cdot d\vec{A}\right)}{dt} = -BL_P\dot{z} \tag{3}$$

where Φ is the magnetic flux density, B is the magnetic field strength of the magnet, L_P is the practical coil length, and $\dot{z}$ is the relative velocity of the tip point of the cantilever with respect to the magnet. The relative velocity term is obtained from the steady state solution of Equation (1) defined above and given by [4],

$$\dot{z}(t) = \frac{\left(\frac{\omega}{\omega_n}\right)^2 \omega Y}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta_{eq}\frac{\omega}{\omega_n}\right)^2}}\cos(\omega t + \varphi) \tag{4}$$

where ω is the vibration frequency, Y is the vibration amplitude, φ is the phase angle, and ζ_{eq} is the overall damping ratio.

After obtaining the mechanical and electrical models, cantilever dimensions and performance parameters are optimized using the Pattern Search Algorithm. This algorithm, mainly finds the *global maximum* of the defined objective function, for example, the induced voltage on the coils in this case. Linear and nonlinear constraints can be defined together with upper and lower bounds of the design parameters. The main advantage of this algorithm is that local minimums are avoided unlike direct line search algorithms. Besides, all the design parameters are considered and optimized at once to give the optimum solution. Table 1 lists important optimized parameters of the micro generator.

Table 1: Optimized parameters of the generator.

Cantilever size (µm)	890x670x15
Natural freq. of cant.	4.53 kHz
Magnet size	4x4x4 mm
Distance btw. cants. to magnet	50 µm
Coil width	20 µm
Coil resistance	110 Ohm
Coil length	14 mm
Overall voltage output	40 mV

As the final step of the design, the stress developed in the cantilevers is considered. Since the cantilevers are loaded by pure bending, only the tensile stress is considered. Tensile stress due to shear will be neglected since it is usually much smaller than the tensile stress due to pure bending. The net force on each cantilever is due to inertial forces only and can be determined from,

$$\sum F = m_{eq}\left(\ddot{z}+\ddot{y}\right) = -\left(b_{eq}\dot{z}+k_{eq}z\right) \qquad (5)$$

The maximum moment, M_{max}, occurs at the support point (fixed end) and defined by,

$$M_{max} = \sum F \cdot L \qquad (6)$$

Thus, the maximum stress will also occur at the support and over the surface of the structure,

$$\sigma_{MAX} = \frac{M_{max}c}{I} \qquad (7)$$

In the last two equations, M_{max} is the moment at the support point, L is the distance between the tip point of the structure to the support, and c is the distance between the neutral axis (centroid of the section) to the surface of the cantilever defined by $c = h/2$. Substituting Equations (5) and (6) in Equation (7) gives,

$$\sigma_{MAX} = \frac{\left(b_{eq}\dot{z}+k_{eq}z\right)Lh}{2I} \qquad (8)$$

Equation (8) gives the tensile stress caused by dynamic motion and static loading. Note that, in this case the dynamic motion is small compared to static loading and can be neglected. When the dynamic part is neglected and $k_{eq} = \frac{3EI}{L^3}$ and $I = \frac{1}{12}bh^3$ are substituted in the final equation, the maximum stress becomes,

$$\sigma_{MAX} = \frac{3Eh}{2L^2}z \qquad (9)$$

For safe operation, $\sigma_{MAX} \leq \sigma_{ALLOWABLE}$ condition must be satisfied and for this purpose, referring to Equation (9), the thickness of the cantilever and the tip displacement should be kept small while the length of the cantilever should be kept as large as possible. Using the design parameters given in Table 1, if the base is excited at a maximum vibration frequency of 6 kHz and an amplitude of 0.7 µm (corresponding to 100g base acceleration) then the cantilever tip point would undergo a transverse deformation of 106 µm for a damping ratio of ζ=0.0033. Under these circumstances, using Equation (9), the maximum stress in the cantilever would be estimated as $\sigma_{MAX} = 10.5\,\mathrm{MPa}$, which is 5.2 times smaller than the allowable yield stress of $\sigma_{ALLOWABLE} = 55\,\mathrm{MPa}$ for Parylene C [3]. As a result, a safety factor of 5 is achieved, which is a reasonable value in terms of mechanic loading.

3. FABRICATION

The micro fabrication steps of the proposed generator are quite easy and require 5 masks. Figure 7 shows the fabrication process [5].

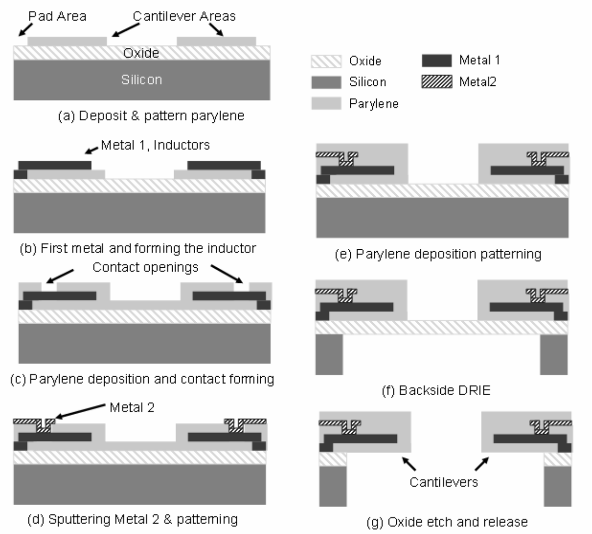

Fig. 7: Fabrication process

4. EXPERIMENTAL RESULTS

Figure 8 shows the photograph of the fabricated prototype prepared for testing.

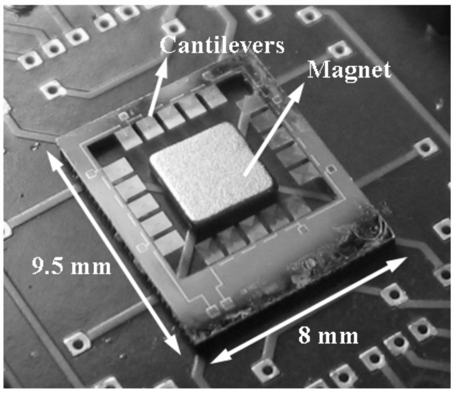

Fig. 8: Photograph of the fabricated prototype.

The tests are carried using a shaker table that is controlled in closed-loop to achieve desired vibration amplitude and frequency. The frequency is swept from 2.5 to 6 kHz at a constant displacement of 0.7 µm. Figure 9 shows the voltage output from the generator with respect to excitation frequency. The prototype generates a maximum voltage of 3.6 mV at a vibration frequency of 4.156 kHz. The bandwidth of the generator is 184 Hz with a damping ratio of 0.022.

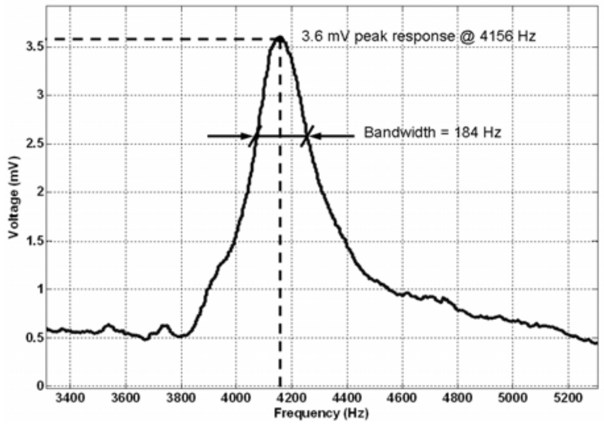

Fig. 9: Measured voltage output.

The generator is designed to have an overall voltage output of 40 mV at a resonance frequency of 4.53 kHz. There are mainly two reasons in the inaccuracy of estimated and measured voltage values. First of all, the mechanical damping ratio is a complex quantity and as it depends on many variables, it is hard to estimate it exactly. Another parameter creating discrepancy is the magnetic flux density; it is estimated assuming that the distance between the coil and the magnet is 50 µm, but since the coils are fabricated *along* the cantilevers' lengths, actual distance is variable and much larger than 50 µm. Discrepancy between the estimated and measured values of the natural frequency is due to 1 µm deviation from the designed cantilever thickness. This deviation occurs due to the inaccuracy in the deposition of parylene. Table 2 lists the properties of the fabricated prototype.

5. CONCLUSION

Design, optimization, and implementation of an electromagnetic micro energy scavenger using an array of parylene cantilevers is presented. The coils located on the cantilevers are connected electrically in series to increase the voltage that is generated by virtue of the relative motion between the coils and the magnet. A detailed mathematical modeling and optimization of the design for various cases are carried out. It has been shown that the micro energy scavenger can generate a maximum voltage of 3.6 mV at a vibration frequency of 4.156 kHz.

Table 2: Parameters of the fabricated prototype.

Size of the device	9.5x8x5 mm^3
Natural freq. of cants.	4.156 kHz
Cant. size (µm)	890x670x16
Number of cantilevers	20
Magnet size	4x4x4 mm
Distance btw. cants. to magnet	900 µm
Coil width	20 µm
Coil resistance	110 Ohm
Coil length	14 mm
Damping ratio	0.022
Max. voltage output	3.6 mV

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