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A MICROMACHINED VIBRATION-INDUCED POWER GENERATOR FOR LOW POWER SENSORS OF ROBOTIC SYSTEMS

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ABSTRACT

This paper presents the design, analysis, and experimental results of a vibration-induced power generator with total volume of ~1 cm^3 that uses laser-micromachined springs as resonating structures. The goal of our research is to create a minimally sized electric power generator capable of producing enough voltage to drive low-power IC circuit systems or micro sensors for robotic and automation applications where mechanical vibrations are present. Potential applications for the generator may also include mobile phone and heart-pacers where human motions can be used as a source of mechanical energy. Thus far, we have produced a generator capable of producing 2V DC with 64Hz input frequency with <200μm input vibration amplitude.

KEY **WORDS:** micro power generator, micro battery, micro energy converter.

INTRODUCTION

One of the projected goals for Microelectromechanical Systems (MEMS) technology is to develop low-cost and high-performance distributed sensor systems for medical, automotive, manufacturing, robotics, and household applications. Ideally, these distributed systems will have their own integrated power supplies to reduce potential problems such as interconnection, electronic noise and control system complexity. Efforts are underway to develop integrated chemically based power supply with MEMS devices. However, where shelf life or replacement accessibility is a limiting factor, chemical power supplies may not be the optimal choice. We propose to build a mechanically based integrated MEMS power generator which will convert vibrational kinetic energy transferred from the immediate environment to electrical energy usable by a low-power CMOS circuit chip and integrated microsensors. Micromachining techniques are used to build the vibration electric power generator because they offer two distinct advantages: 1) precise control of the mechanical resonance which is necessary to produce an efficient generator, and 2) batch fabrication which will allow low-cost mass production of commercially viable generators. The current trend in very large scale integration (VLSI) circuits design is in minimization of power consumption to extend battery life in portable systems and heat removal in larger systems. Coupling with the recent advent in low-power MEMS sensors, a MEMS integrated mechanical power generator with life span far greater than its chemically based counterparts will be imperative in diverse sensor and circuit applications in the near future.

Various integrated micro power supplies have been proposed recently. Matsuki et al. used an energy coupling method to remotely induce voltages on-chip by magnetic field in 1988 [1]. Bates et at. developed rechargeable lithium micro batteries which were used as self-contained on-board power supply in 1993 [2]. Rashidian & Allen also showed that electrothermal micro actuators could be driven remotely by high frequency electric field in 1993 [3]. Lee et al. built a miniaturized high-voltage solar cell array which was effective in driving electrostatic silicon mirrors in 1995 [4]. A comprehensive study on the feasibility of micro power supplies for MEMS was presented by Koeneman et al. in 1997 [5], who concluded that the most practical forms of micro energy storage media are chemical batteries, elastic

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strain energy, electric fields, and magnetic fields. However, there are many applications where light, thermal, electrical, or magnetic energies are not practical or available, therefore, we propose a new power supply which is integrable with MEMS and IC devices, and which generates electricity from ambient mechanical vibrations.

Shearwood & Yates [6] and Williams and Yates [7] developed an electromagnetic micro generator that attached a magnet to a flexible polyimide membrane to produce 0.3μW on a planar pick-up coil in 1997. No structural optimization or integration of their generator to a circuit system was reported. Amirtharajah & Chandra-kasan [8] have successfully used a *macro* (500mg mass) vibration-based power generator to drive a signal processing circuitry in 1998. They integrated an ultra-low-power controller and a low-power subband filter load circuit on to a CMOS chip which consumes 18μW of power. To the best our knowledge, no one has published a work combining a MEMS resonating system and a low-power circuit system with optimized mechanical structures for specific applications. For this project, we propose to develop an integrated, efficient, and robust vibration-based power generator suitable for low-power sensor and circuit systems.

POWER GENERATION FROM MECHANICAL EXCITATION

System Analysis Using Frequency Domain Approach

A simple power-generation model analysis using frequency domain approach is presented below for the sake of understanding the importance of the governing physical parameters of the system. A schematic illustration of the system is shown in Figure 1 and a possible integrated spring-mass power generation system is shown in Figure 2. The voltage generated on the wire coil is modeled by a first order LR circuit which takes the magnet motion z as input. The governing physical parameters are the mass of magnet m, magnetic flux ***B***, spring constant ***k***, inductance of the coil ***L***, and resistance of the coil ***R*.,** and the load resistance ***R***. In addition, the housing vibration amplitude ***y(t)*** and frequency w will affect the relative magnet vibration amplitude *z(t)*, which consequently affects the power output of the system. The transfer function from the input force to the mass displacement relative to the wire coil is [9]:

$$z(s)/F(s) = 1/ms^2 + cs + k \qquad \textbf{Eq. 1}$$

The behavior of the electrical system is described by the following differential equation, in which *I(t)* is the current passing through the wire coil.

$$L\dot{I}(t) + (R + R_c)I(t) = Bl\dot{z}(t) \qquad \textbf{Eq. 2}$$

In the above equation, it is assumed that the output voltage generated across the load resistor from the coil and a moving magnet is $V = Bl\dot{z}$ [10]. Then, the transfer function from the relative displacement of the mass to output voltage at the load resistor, including the coil resistance and inductance is:

$$V(s)/z(s) = [BlRs]/[Ls + R + R_c] \qquad \textbf{Eq. 3}$$

The feedback electromechanical force generated by the induced current in the wire coil is derived as [1 O]

$$f_e = BlI = (Bl/R)V \qquad \textbf{Eq. 4}$$

Combining equations 1,3, and 4, the transfer function from the input force to the output voltage in frequency domain can be written as:

$$V(s)/F(s) = [BlRs]/\left[(Ls + R + R_c)(ms^2 + cs + k) + (Bl)^2 s\right] \qquad \textbf{Eq. 5}$$

The block diagram for this system is shown in Figure 1.

Since the inductance of the coil is small and the load resistance is large, the ***L/R*** time constant is short. If the mechanical constants are chosen such that the resonant frequency of the system are the same as the input excitation, the mechanical time constant will be much greater than the electrical one. Hence, it is reasonable to ignore the electrical pole and treated the system as a damped second order system [8].

Moreover, by assuming that both L and R_c are negilible as stated, the system transfer function may be rewritten as:

$$V(s)/F(s) = Bls/(ms^2 + ds + k) + s(Bl)^2/R \qquad \textbf{Eq. 6}$$

Now, a damping factor ξ can be defined and which be decomposed into a mechanical damping factor ξ_m and an electrical damping factor& such that:

$$\xi_m = c_m/\sqrt{2mk} = c_m/2m\omega_n \qquad \textbf{Eq. 7}$$

where c_m = c, is just the spring-mass system damping coefficient (from Equation 1). Also,

$$\xi_e = (Bl)^2/2R\sqrt{mk} = \left((Bl)^2/R\right)/2m\omega_n \qquad \textbf{Eq. 8}$$

So, the equivalent electrical damping coefficient for the generator system is $(Bl)^2/R$. Equation 9 becomes:

$$V(s)/F(s) = [s\ Bl/m]/s^2 + 2\xi\omega_n s + \omega_n^2 \qquad \textbf{Eq. 9}$$

Now, the output voltage can be solved as a function of a sinusoidal input force. By the simple relationship $P(t) = V^2(t)/R$, and the taking the limit of time to infinity, the average power output of the generator system is derived as:

$$P = m\xi_e Y_0^2 (\omega/\omega_n)^3 \omega^3 \Big/ \left(\left[1 - (\omega/\omega_n)^2\right]^2 + (2\xi\ \omega/\omega_n)^2 \right) \qquad \textbf{Eq. 10}$$

From the above equation, at resonance, the average power and the voltage output are maximized

$$P = m\xi_e Y_0^2 \omega_n^3/4\xi^2 \quad \text{and} \quad V_0 = \sqrt{2PR} = BlY_0\omega_n/2\xi \qquad \textbf{Eq. 11}$$

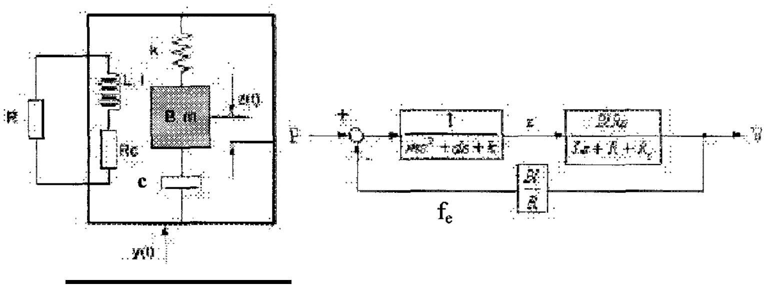


Figure 1. Transfer function block diagram for the micro power generator.

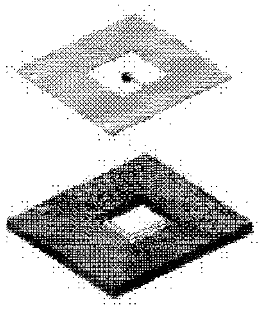


Figure 2. Proposed design of an integrated micro power generator.

Design Objective

Since the applications for micro power generators abound we will only constrain the current analysis to the design of a generator which is small and able to generate usable electrical power under typical human activities. So, the question which needs to be answered is: what is the smallest generator possible which can generate 1V for a system consuming 30μW power at input frequencies ranging from 2 to 10 Hz (i.e., human walking or running) using conventional MEMS technology? Our goal is to create an integrated system which contains the resonating spring, the coil (as shown in Figure 2), and the IC or micro sensor chip.

Silicon Springs for Low Vibration Systems?

If the mass of magnet is known (governed by state-of-the-art technology for small volume and high field strength material) and assuming all mechanical power can be converted into electrical power (assume 30μW is needed to run a given IC system), then Equation 11 can be used to find the resonant amplitude of the spring at a given input vibrational frequency (Figure 3). So, a spring must, minimally, be able to withstand deflection at this amplitude if it needs to generate the required power. Now, the spring constant $\boldsymbol{k}$ and the mass $\boldsymbol{m}$ have the relationship $\sqrt{k/m}$ at resonant angular frequency ω_n, hence, if the input frequency is given, a spring can be designed to have resonance at that frequency. Then, if the length and width of the spring are given, the thickness of the spring can be designed to achieve a given ***k***. Moreover, if the yield stress of a structural material is known, the maximum deflection allowed for a given spring design can also be found. We have assumed the length of the spring is fixed at 5000μm (allowing the magnet to be centered on a 1cmx1cm chip as shown in Figure 2) and the width is 100μm (conservative estimate for Si bulk-micromachining technology), then the allowable deflection of a spring and its thickness can be found as a function of input frequency. This analysis is shown in Figure 3 for silicon and copper. Clearly, for a 1 cmx 1 cm system with 30μW power output, a Si cantilevered beam can not achieve the <10Hz requirement, because it can not achieve the required amplitude without structural damage. On the other hand, copper is a very good material, because it is non-magnetic, has low spring-constant, and high yield stress, for low frequency resonance power generation. As shown in Figure 3, the allowable deflection exceeds the required deflection even a 2Hz vibration. Also, the required thickness of copper for this deflection is ~10μm, which is readily available commercially.

In addition, as implied by Figure 1, many parameters govern the optimization of a generator even if the size of the generator is known a priori. These parameters are listed in Table 1. As an example, the dependence on voltage output versus coil length and input vibration frequency is shown in Figure 4. In general, even though voltage output can be maximized by increasing input frequency, precise coil length is critical in optimizing the voltage output, especially for higher frequency vibrations.

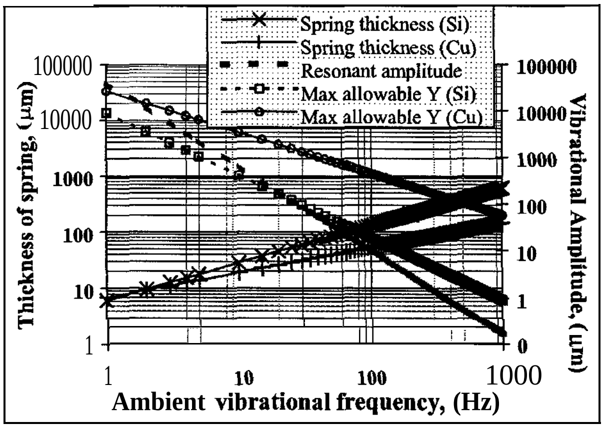


Figure 3. Analysis of spring thickness requirement and Maximum allowable deflection as functions of ambient Vibrational frequency.

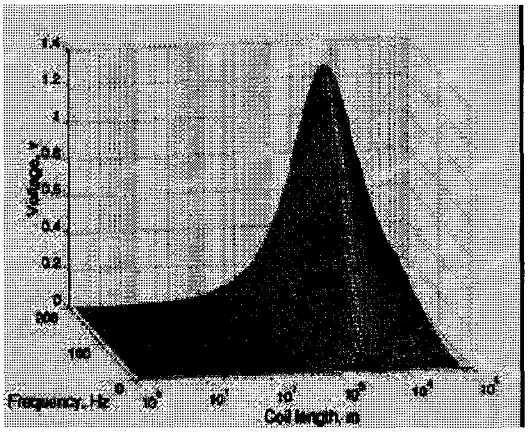


Figure 4. Voltage output versus vibrational frequency and coil length.

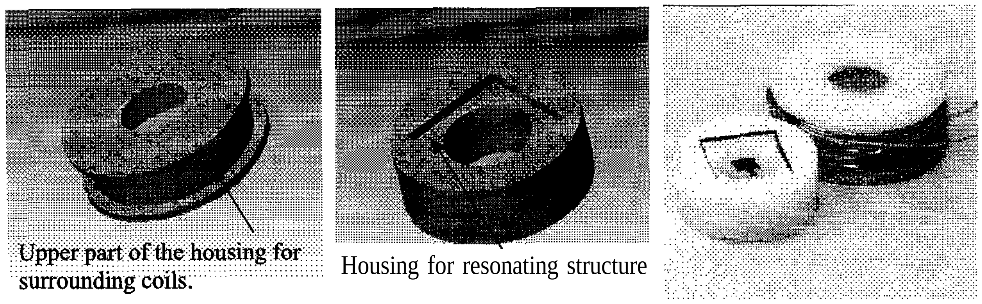
F	Generator input force	*d*	Mechanical damping coefficient	*B*	Magnetic field strength of magnet
y	Generator input displacement	*l*	Length of wire coil	*k*	Spring constant of springs
z	Mass displacement relative to coil	*R*	Load resistance	m	Mass of magnet
V	Voltage output at load resistor	*L*	Coil inductance	*k*	Spring constant of springs
f^{u}	Feedback electromechanical force	R_c	Coil resistance	ω_n	Spring natural frequency

Table 1. List of variables critical to the performance of the power generator.

FABRICATION OF THE POWER GENERATOR SYSTEM

Prototype Housing for Spring and Coil

The prototype for the generator is shown in Figure 5. The current generator system is composed of 4 parts: the micromachined spring, the coil, an outer housing for the coil, and an inner housing for the resonating spring structure. The housing is produced by a rapid prototyping machine (StrataSys FDM 1600 RP Machine) using ABS plastic. The entire housing has a diameter of 1.5cm, a height of 0.7cm, and allows 1500 turns of insulated coils (50μm diameter).

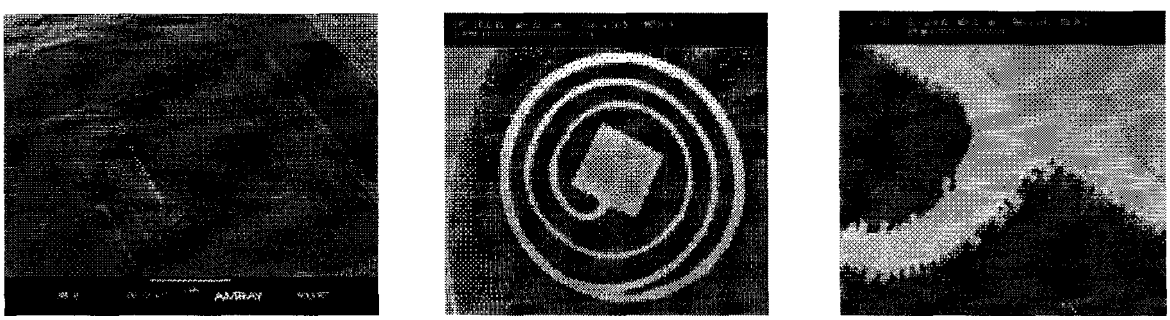


(a) (b) (c)

Figure 5. (a) Upper (outer) part for the coil. (b) Inner part for spring structure. (c) Picture of a generator. Part (a) is hollow for part (b) to fit inside it.

Fabrication of the Spring Structures

We have used both Si bulk-micromachining and laser-micromachining to fabricate the spring structures. A Si micromachined spring structure is shown in Figure 6a. The structure shown has supporting beams of 100μm thickness, 300μm width and 2mm length. We have found that Si springs are very fragile to environmental vibrations and are easily damaged during handling and sudden shock. As discussed in the previous section, copper springs are more suitable for low-frequency energy conversion. We have used a Nd:YAG laser (Electrox) to micromachine copper spring structures. A 5mm diameter resonating structure is shown in Figure 6b. As indicated by Figure 6c, the laser gives rough vertical surfaces if the power, pulse rate, and scan speed are not optimized. We are now working on optimizing these parameters to obtain smooth vertical side walls for the copper resonating structures as rough walls may affect the designed resonant frequency of the structures.



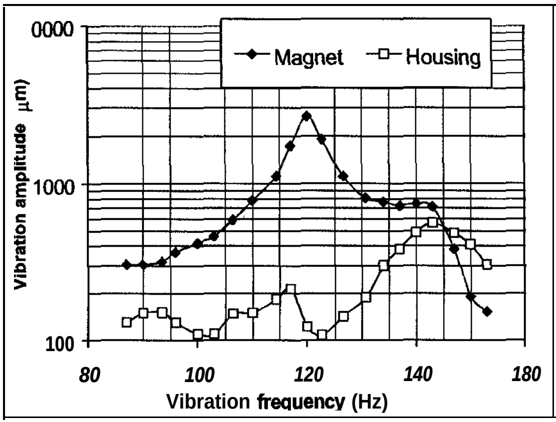
(a) (b) (c)

Figure 6. (a) A bulk-micromachined Si spring structure. (b) A Laser-micromachined Cu spring structure. The diameter of the entire structure is 5mm. (c) Close-up view of the structure in (b). The width of the spiral-structure is about 100μm.

EXPERIMENT RESULTS

Input Vibration and Power Output

A 21 0mg magnet (Rare Earth permanent magnet of ~2000Gauss) is put at the center of a spring structure (similar to the one shown in Figure 6b), and vibrated at different frequencies. In our experimental set up, the vibrational input amplitude varies with the input frequency. The measured vibration amplitude of the housing and the spring-magnet structure is shown in Figure 7. Even though the input amplitude varied from 100 to 600μm over the given frequency range, clearly, the resonant frequency for the structure tested is at120Hz. The peak-to-peak AC voltage generated using this same structure is shown in Figure 8 (80mV output with 2.7mm amplitude at 120Hz).



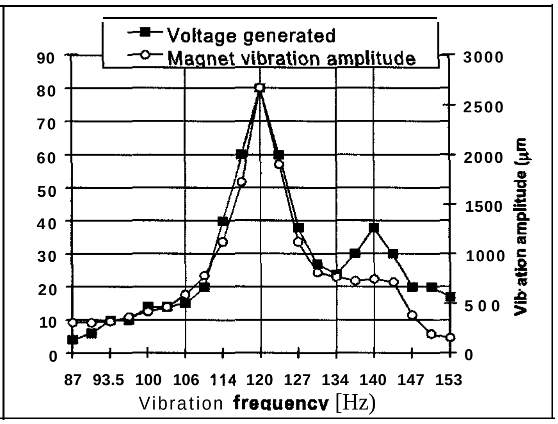
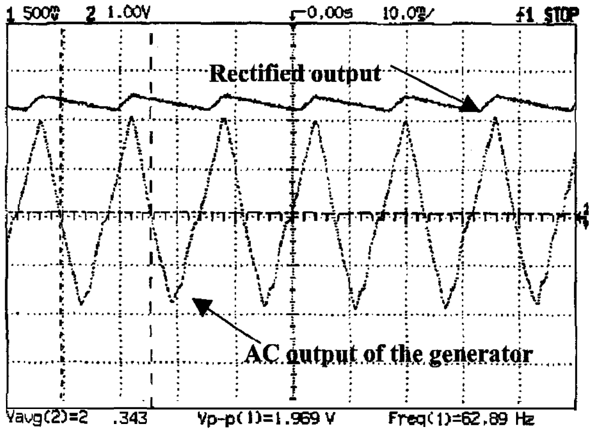


Figure 7. Vibration amplitude of the housing on top of the vibration drum.

Figure 8. Voltage output and the vibration amplitude versus input frequency of an cantilever structure.

DC Voltage Conversion

We have used a 1cm diameter copper spring structure with 500µm wide spirals to generate ~2V peak-to-peak AC voltage as shown in Figure 9. However, to be useful to electrical systems, the voltage generated should be in DC. A voltage rectifier was used (Figure 10) to convert the AC voltage into DC output (Figure 9). As shown in Figure 9, the rectified DC voltage is above2V. We are currently in the process of testing commercial chips which can be powered by this voltage level.



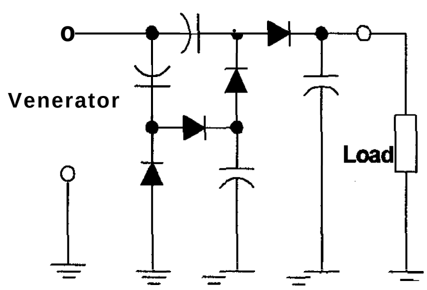


Figure 9. AC Voltage output of the generator (input vibration at 64Hz, 100µm amplitude) and DC output after rectifying the AC signal.

Figure 10. A *quadrupler* voltage rectifier to convert the AC voltage into DC output.

CONCLUSION

This paper presented the design, modeling, and analysis of a meso-scale generator with laser micromachined spring structures that converts mechanical vibrations into electrical power. The prototype generator is able to generate 10µW power at 2V DC with an input excitation frequency of 64Hz and amplitude of100µm. Some mechanical structures have been studied to optimize the spring constant for different environmental excitation. Future work for this project include 1) improvement of the micro generator by optimizing the damping factor of the system, 2) reduce resonant frequency of the spring structure, and 3) integrate the generator to CMOS chips. A comparison of the performance of our generator versus two other groups which published their work recently is given in Table 2.

Research Group	Coil (No. of Turns)	Magnet Mass (mg)	Magnet Size (mm)	ω_n (Hz)	z (μm)	V (mV)	Power output (μW)
M. I. T. [8]	?	500	5x5x?	100	?	180	10^2*
Sheffield [7]	13	2.4	3x3x?	4400	10^{-1}	?	0.3
A.M. L.	1500	210	3x3x3	64	1000	2000DC	10

Table 2. Comparison of current results, (* With a large impulsive excitation.)

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