Infrared Signal Transmission by a Laser-Micromachined Vibration-Induced Power Generator

Wen J. Li, Terry C. H. Ho, and Gordon M. H. Chan
The Chinese University of Hong Kong
Dept. of Automation and Computer-Aided Engineering
MMW Bldg., Room 425
Shatin, NT, Hong Kong
Email: wen@acae.cuhk.edu.hk

Philip H. W. Leong, and Hiu Yung Wong
The Chinese University of Hong Kong
Dept. of Computer Science and Engineering
HSH Eng. Bldg., Room 1028
Shatin, NT, Hong Kong
Email: phwl@cse.cuhk.edu.hk

***Abstract*–This paper presents the development of a vibration-induced power generator with total volume of ~1cm^3 that uses laser-micromachined springs to convert mechanical energy into useful electrical power. The goal of this project is to create a minimally sized electric power generator capable of producing enough voltage to drive low-power ICs and/or micro sensors for applications where mechanical vibrations are present. Thus far, we have developed a generator capable of producing 2V DC with 64Hz to 120Hz input frequency at ~250μm vibration amplitude. We have also demonstrated that this generator has enough power to drive an IR transmitter to send 140ms pulse trains with ~60sec power generation time.**

***Index Terms*—micro power generator, micro vibration-based power generation, micro power supply.**

I. Introduction

One of the projected goals for Micro-electro-mechanical 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 that will convert vibrational kinetic energy transferred from the immediate environment to electrical energy usable by a low-power ICs or integrated micro sensors. Some pioneering work were done by researchers at the University of Sheffield [1] and Chandrakasan's group at MIT [2]. Nevertheless, to the best of our knowledge, no one has demonstrated a micromachined generator with enough power to drive an off-the-shelf circuit.

For our work, micromachining techniques are used to build the vibration-induced 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 design analysis and experimental results for our first generation micro power generators are presented in this paper.

This project was funded by the Hong Kong Research Grants Council (Earmarked Grant no. 2150201).

II. Generator Concept and Design

A conceptual drawing of the micro electromagnetic generator is shown in Fig. 1. The device consists of a permanent magnet of mass m with magnetic field strength B, springs with total spring constant k, and a wire coil of length l. The ends of each spring are attached to the permanent magnet and a solid frame, which is connected to the rigid housing of the device, forming a mass-spring resonator structure. The electrical coil is fixed on the rigid housing of the device. When the rigid housing is vibrated, the magnet will move relatively to the housing and the wire coil. This relative movement of magnet to the coil results in the varying amount of magnetic flux passing through the coil. According to Faraday's Law of induction, which states that the electromotive force induced is equal to minus the rate of change of the flux linkage when the magnetic flux passing through an area enclosed by a loop changes, a voltage is induced on the coil.

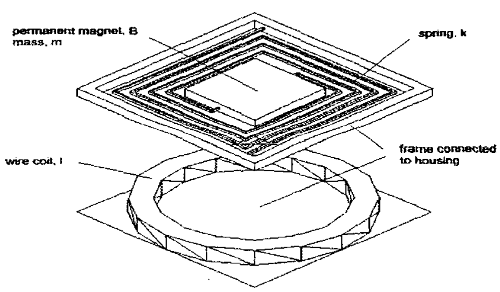


Fig. 1. Time-sequenced pictures showing the horizontal motion of the generator mass due to a vertical input excitation.

A. System Modeling

The average power output of the system shown in Fig. 1 can be derived as [3]:

$$P = m\xi_e Y_0^2 (\omega/\omega_n)^3 \omega^3 \Big/ \left(\left[1 - (\omega/\omega_n)^2\right]^2 + (2\xi\,\omega/\omega_n)^2 \right) \qquad (1)$$

where ω is the input vibration frequency (angular), ω_0 is the resonant frequency of the spring-mass system, Y_0 is the vibration amplitude at resonance, ξ_e is the electrical damping factor, and ξ is the total damping factor of the system. From the above equation, at resonance, the average power output is maximized:

$$P = m\xi_e Y_0^2 \omega_n^3 / 4\xi^2 \qquad (2)$$

Hence, to maximize the power or voltage of the generator, electrical damping and resonate amplitude should be maximized

Proc. 43rd IEEE Midwest Symp. on Circuits and Systems, Lansing MI, Aug 8-11, 2000
0-7803-6475-9/00/$10.00 ©IEEE 2000

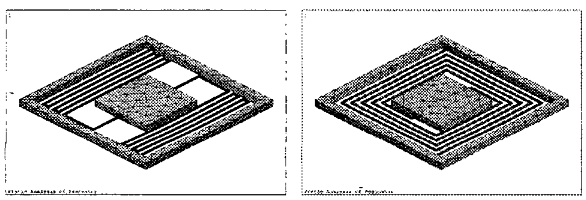
at any given vibration input frequency.

B. Spring Design

In designing the mechanical resonating spring, few factors should be considered: the structure should resonate with large amplitude with small input vibration amplitude, it should have long fatigue life, and it should compatible with micromachining processes.

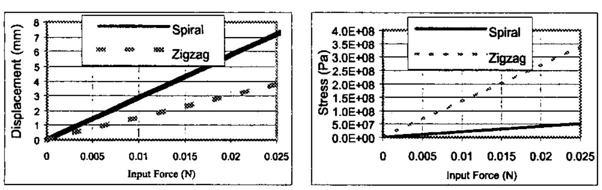
1) Spring Geometry: A spiral structure (Fig. 2a) with total spring length l=70.1mm and a zigzag structure (Fig. 2b) with length l=76.9mm (these dimensions were chosen so that planar springs of 100µm width can be fabricated within 1cmx1cm surface area) were studied to compare spring deflection and stress under a giving applied force at the center of the mass held by the springs. ANSYS results indicate that spring pattern in the spiral form are able to provide twice as much deflection (k=3.47N/m) as those in zigzag form (k=6.64N/m), while experience only ~15% of the bending stress (Fig. 3).

2) Spring Material: Copper was chosen over silicon as the spring material because it has lower spring constant which will give larger vibration amplitude, it has longer fatigue life, it is fabricable with various micromachining technologies, and it is integrable with conventional electrical technology such as PCB fabrication process. A more detail analysis on material selection is given in [4].



(a) (b)

Fig. 2. Two examples of spring designs for the generator. (a) A "zig-zag" spring. (b) A "spiral" spring.



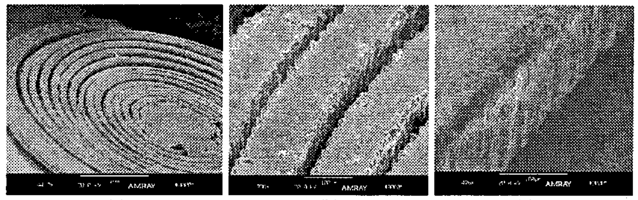
(a) (b)

Fig. 3. ANSYS results: (a) Displacement of springs versus input force. (b) Stress on the springs due to input force. The spiral design is conclusively better than the zig-zag design because of its higher amplitude and lower stress.

III. Spring Fabrication and Testing

A. Laser-micromachining of Copper Springs

Based on the ANSYS results we have used a Q-switch Nd:YAG (1.06µm wavelength) laser to micromachine copper spiral spring structures as shown in Fig. 4. Currently, we are able to produce spring structures with total diameter ranging from 4mm to 10mm and have spring gap/width dimensions ranging from 40µm/40µm to 100µm/100µm, using 110µm thick copper. However, laser parameters such as pulse-frequency, cutting speed, and power will affect the precision and resolution of the copper spring geometry (see Fig. 4b and Fig. 4c) which may influence the designed resonance of the spring-mass system, hence, we are currently investigating the optimum parameters for laser-micromachining of copper thick films.



(a) (b) (c)

Fig. 4. Laser-micromachined copper springs. (a) A planar copper spring with total diameter of 4mm. (b) Close-up of the spring shown in (a) – the sidewalls are jagged. (c) Close-up of a spring cut with different laser parameters – the sidewalls are smoother than the spring shown in (b).

B. Spring Vibration Test Results

Prototypes of the generator were tested using a *4809 Brüel Kjær Vibration Exciter* with input frequency ranging from 1 to 130Hz with amplitude of ~250µm. A *Polytec OFV303* laser pointer and an *OFV3001 Vibrometer* were used to measure the absolute vibration amplitude of the generator and the magnetic mass connected to the spring. Details of the experimental setup is given in [3]. An interesting experimental observation on the generator output voltage versus mass vibration amplitude was made: as shown in Fig. 5 for a particular resonating spring, the generator gave relatively high voltage at higher frequencies even though the vibration amplitude is almost negligible in the vertical direction. Using a strobe light to synchronize the vibration motion of the mass, the mass was observed to have a 2nd and 3rd mode resonance. The mass appeared to cyclically rotate about an axis parallel to the plane of the coil. Furthermore, it was observed that the amplitude of the rotation is very small compared to the vertical vibration at the 1st mode resonance. We therefore conjecture that if the a spring can be designed to vibrate in a horizontal plane rather than a vertical plane relative to a coil, even under a force in the vertical direction, the voltage output can be increased and the stress on the spring can be reduced. Physically this can be explained by the fact that Faraday's Law predicts the voltage output to be proportional to the rate of changing magnetic flux, and hence, a region of greater flux density will allow for greater current induction. In other words, when the magnetic mass moves too far away from the coil, the flux density is low and the rate of changing flux decreases significantly.

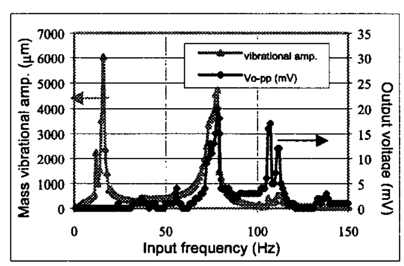
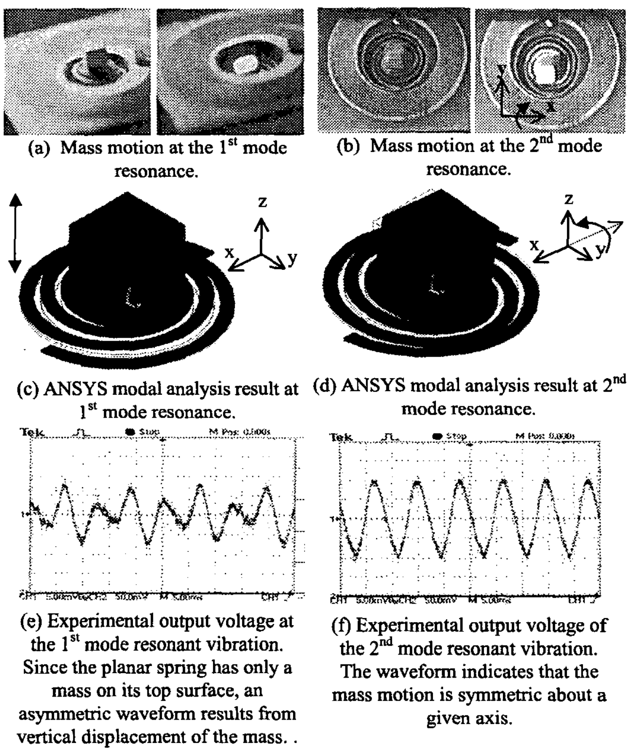


Fig. 5. Vibrational amplitude of the mass and the resulting voltage generated for a 2DOF spring structure.

We have used ANSYS to model the mechanical motion of the resonating spring-mass system and matched the results with the above experimental observations. The motion of the mass during 1st, 2nd, and 3rd mode of resonance were captured on digital video and compared to ANSYS modal analysis results. Samples of comparison are shown in Fig. 6 below. Details of the ANSYS modeling and analysis can be found in [4]. According to the modal analysis results, the 1st mode occurs at 81.5Hz, which corresponds to the experimental output voltage peak at 70~80Hz in Fig. 5. The power output is from the resonant vertical movement of the magnet at this frequency. Repeated measurements showed the 2nd peak to be at 107Hz and 3rd peak at 113Hz. However, unlike the 1st mode where large vertical deflections were observed, the vertical magnet vibration amplitude is small (~300μm) at these mode frequencies. Instead, an oscillatory motion about an axis in the plane of the coil was observed at the 2nd mode resonance. Hence, it is clear that the voltage peak occurring at the 2nd mode frequency is not contributed by the vertical spring vibration as designed. Modal analyses reveal the occurrence of the 2nd mode frequency at 131.5Hz. The rotation of the magnet is much larger than the vertical deflection at this driving frequency such that a large power is generated even with a small input amplitude (~200μm).



(a) Mass motion at the 1st mode resonance.
(b) Mass motion at the 2nd mode resonance.
(c) ANSYS modal analysis result at 1st mode resonance.
(d) ANSYS modal analysis result at 2nd mode resonance.
(e) Experimental output voltage at the 1st mode resonant vibration. Since the planar spring has only a mass on its top surface, an asymmetric waveform results from vertical displacement of the mass. .
(f) Experimental output voltage of the 2nd mode resonant vibration. The waveform indicates that the mass motion is symmetric about a given axis.

Fig. 6. Experimental and ANSYS results.

The 3rd mode can be treated as an extension of the 2nd mode. The 3rd mode frequency is closed to the 2nd mode frequency in that it is sometimes undetectable during the experiment. Modal analyses reveal the 3rd mode frequency to be at 135.59Hz. From experimental observations, the mass rotates resonantly about the x-axis at 2nd mode frequency (Fig. 6b), but when the input frequency is increased, the axis of rotation begins to shift towards the y-axis about the z-axis, resulting in a decrease of voltage output. The power generated by the generator continues to drop and then rise until reaching a vibration resonant frequency of 113Hz. The magnet vibrates resonantly about an axis 45 degree to the x-axis horizontally at this frequency, resulting in a local maximum voltage output. A summary of the experimental and ANSYS results are given in Table 2. The discrepancy between ANSYS and measured results is most likely due to the imprecise packaging technique, i.e., magnetic mass is attached to the spring by epoxy without accurate alignment procedures, which will cause a shift of resonant frequency. We are currently developing a better packaging technique to overcome this problem.

TABLE I

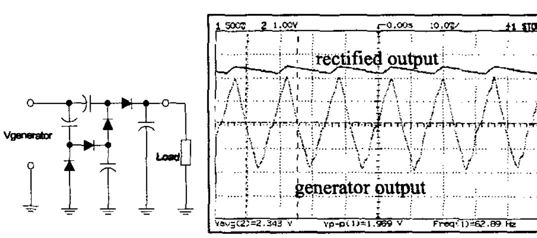
PERFORMANCE OF QUADRUPLER WITH 1.16MF CAPACITIVE LOAD.

Mode	Experimental Freq. (Hz)	ANSYS Freq. (Hz)	Mode shape
1	80	81.53	Pure vertical translation about z.
2	107	131.50	Rotation about horizontal axis x.
3	113	135.59	Rotation about a horizontal axis between x and y axes.

IV. IR SIGNAL TRANSMISSION

A. Voltage Rectification

Thus far, we have fabricated generators with total volume of 1cm^3 or less that are capable of producing up to 4V AC with instantaneous peak power of 80mW, at input frequencies ranging from 60 to 120Hz with ~200μm input vibration amplitude. However, most generators do not have sufficiently high voltage to power even low voltage electronic circuits so a voltage multiplier was used to step up the AC voltage. A standard quadrupler circuit (Fig. 7a) was used to step up the AC output from the generator to DC voltage (Fig. 7b). A prototype of this circuit was built using 10μF, 25V electrolytic capacitors and *Motorola Inc 1N5817RL* Schottky diodes which have a forward voltage of 0.32V. The output of the generator dropped to 1.3*V* when loaded and to 0.448*V* when the quadrupler was incorporated. This could be reduced by better impedance matching between the generator and the quadrupler. However, the multiplied output DC voltage of 2.3V is sufficient to drive most low voltage circuits. The measured average current was 40μA, and hence the power output for this system is ~100μW.



(a) (b)

Fig. 7. (a) The quadrupler rectifying circuit. (b) Rectified output.

B. IR Signal Transmission

An Infrared (IR) transmitter was built using a commercial *SM5021* encoder chip (Fig. 8). We have experimentally determined that this circuit could operate properly with a power supply as low as 1.8V. Since the output current from the micro generator system (generator plus the rectifier) was too small (40μA) to directly power the chip, the system was first used to charge up a large capacitor, which in turn was used to power the

IR transmitter. An IR signal would be sent to a receiver every time a key was pressed. The signal was a 140.8ms long IR pulse train. For a 2.0V power supply, the current drawn during a key press was measured to be 1.5mA and, in standby mode, 2.4μA. The minimum capacitance required to support a pulse train transmission can be calculated as

$$C = \frac{Q}{\Delta V} = \frac{1.5mA \times 140.8ms}{2.0V - 1.8V} = 1.056mF$$

The time required to charge up this circuit could be calculated as

$$\frac{\Delta V \times C}{I} = \frac{2V \times 1.056mF}{40\mu A} = 52.8s$$

A capacitor of 1.16mF was used as the power reservoir in the experiment. It was first charged up to 2.0V and used to power the transmitter. It took 58 seconds to charge the capacitor from 0V to 2.0V and the charge stored is enough for 2 key presses whereupon the output voltage drops to 1.56V. It would take another 30 seconds to charge it back to 2.0V.

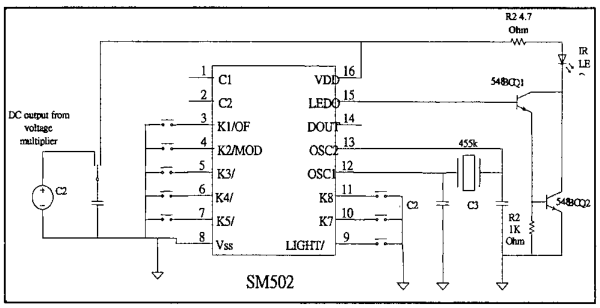


Fig. 8. Diagram of the commercial SM5021 encoder chip.

V. Conclusion

We have developed a micro power generator with laser micromachined copper resonating spring that uses Faraday's Law of Induction to convert mechanical energy into electrical energy. ANSYS analyses were performed to obtain structural designs for the resonating springs. We have found that, by innovative spring designs, the mass can be made to vibrate horizontally while the input vibration is applied vertically, and that this horizontal vibration gives significantly higher output voltage for the generator. MATLAB was also used to simulate the micro generator system output voltage and agreed with experimental results well. These modeling and simulation tool will greatly enhance our capability in designing and optimizing generators for different engineering applications. Currently, for a generator with total volume of $1cm^3$ or less, AC output of 2 to 4V is possible between input frequencies of 60 to 120Hz with no more than 300μm input vibration amplitude. For a resonating spring-mass at ~60Hz, we have demonstrated that its AC output can be rectified to 2V DC by a quadrupler and have used this DC output to drive a commercial *SM5021* encoder chip for IR transmission. The transmitter was able to send 140ms pulse trains with ~60sec of power generation.

Future work for this project include 1) design and develop low resonant springs with the aid of our ANSYS model, and 2) fabricate the spring-mass and coil with an integrated process using optimized coil length, and 3) integrate the generator with IC/MEMS low-power and sensors. We believe that with the current trend in VLSI circuits design to minimize power consumption, our micro generator will find many applications, especially in the fast growing field of distributed sensing systems.

Acknowledgment

We would like to thank the Hong Kong RGC (Earmarked Grant code no. 2150201) for funding this project. We also deeply appreciate Magtech Industrial Company (Hong Kong) for donating and fabricating the magnets needed for this project – without their involvement the high output voltage would not have been possible. Special thanks are also due to Julia S. J. Qin and Neil N. H. Ching for their contributions to this project.

References

[1] C. B. Wiiliams and R. B. Yates, "Analysis of a micro-electric generator for microsystems", *Sensors and Actuators*, A 52, pp. 8 - 11, 1996.

[2] R. Amirtharajah, and A.P. Chandrakasan, "Self-powered signal processing using vibration-based power generator", *IEEE J. of Solid-State Circuits*, Vol. 33., May 1998 , Pp. 687 –695.

[3] W. J. Li, Z. Y. Wen, P. K. Wong, G. M. H. Chan, P. H.W. Leong, "A micromachined vibration-induced power generator for low power sensors of robotic systems", *Proc. of the World Automation Congress*, Hawaii, USA, June 11-14, 2000.

[4] W. J. Li, G. M. H. Chan, N. N. H. Ching, P. H. W. Leong, and H. Y. Wong, "Dynamical modeling and simulation of a laser-micromachined vibration-based micro power generator", Accepted, *Int. J. Non-linear Science and Simulation*, August, 2000.