AN ELECTROMAGNETIC MICRO POWER GENERATOR FOR LOW FREQUENCY ENVIRONMENTAL VIBRATIONS BASED ON THE FREQUENCY UP-CONVERSION TECHNIQUE

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ABSTRACT

This paper presents an electromagnetic (EM) vibration-to-electrical power generator, which can efficiently harvest energy from low-frequency external vibrations by using frequency up-conversion. The generator can effectively scavenge energy from low frequency environmental vibrations of 70-150 Hz and generates 0.57 mV voltage with 0.25 nW power from *a single cantilever* at a vibration frequency of 95 Hz. The fabricated generator size is 8.5 x 7 x 2.5 mm^3 and a total number of 20 serially connected cantilevers have been used to multiply the generated voltage and power. The performance of the generator is also compared with a same sized traditional magnet-coil type generator to prove its effectiveness.

INTRODUCTION

MEMS based energy harvesting from environmental vibrations has been an attractive topic and is extensively investigated since 1995 [1]. The maximum generated power for the traditional techniques is proportional to the cube of the vibration frequency [2] and drops dramatically at low frequencies (1-100Hz). However, it is at these low frequencies where most ambient vibration exists. For this reason, vibration based resonant generators are effective at frequencies of several kHz, and at lower frequencies they are ineffective [3]. The proposed electromagnetic generator solves this problem by mechanically up-converting the low frequency vibrations to a higher frequency. This technique has been firstly proposed by Kulah et al. with a milli-scale implementation [4]. In this paper, a micro scale implementation with experimental results is presented for the first time in the literature. The effectiveness of the energy generation of the proposed design has been experimentally verified through comparative tests with a same-sized traditional magnet-coil type generator.

DESIGN

Figure 1 shows the proposed system, which is composed of two mechanical structures: 1) the upper diaphragm and 2) the array of cantilevers located right below the diaphragm. The diaphragm is made of parylene C and holds a NdFeB magnet for both frequency up-conversion and power generation by means of electromagnetic induction. The diaphragm-magnet assembly resonates by vibrations in the range of 1-100 Hz. The cantilevers have a higher resonance frequency of 2-3 kHz and each of them has a coil for induction. Also, at the tip of each cantilever, nickel is electroplated for interaction with the magnet. As the diaphragm resonates in response to external vibrations, it gets closer to the cantilever array. The distance between them is adjusted such that the magnet *catches* the cantilevers at a certain instance of its movement, pulls them up, and releases at another point. Afterwards, the released cantilevers start resonating at their damped natural frequency with the given initial condition, and hence the frequency up-conversion is realized. The motion of the released cantilevers exponentially decays out and before it completely dies, the cycle starts again.

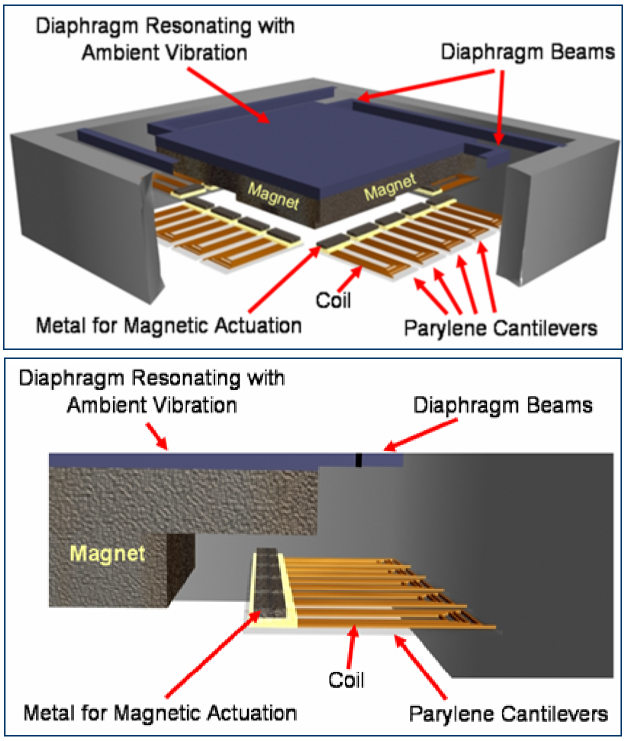

Figure 1: Schematic view of the proposed design: isometric (top) and side (bottom) views.

The equivalent mechanical model of the system is shown in Figure 2, where m, k, and b denote the equivalent mass, stiffness, and damping constants, respectively. The position coordinates are defined by z and δ, with z corresponding to the relative displacements with respect to the base, and δ to the initial offsets with respect to the base. The system is excited by environmental vibrations of frequency ω and displacement amplitude of y. The excitation frequency is close to the natural frequency of the diaphragm-magnet assembly and much smaller than the natural frequency of the cantilevers. This causes only the diaphragm- magnet to be excited by environmental vibrations, and the cantilevers to be remained unaffected. Using this model, the magnet-diaphragm and the cantilever dynamics can be expressed with the following two equations. These equations are the second-order, linear differential

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equations of motion for the magnet-diaphragm assembly, and the cantilevers and are obtained by following an equivalent modeling approach.

$$m_m\ddot{z}_m + b_m\dot{z}_m + k_m z_m = -m_m\ddot{y} \qquad (1)$$

$$m_c\ddot{z}_c + b_c\dot{z}_c + k_c z_c = 0 \qquad (2)$$

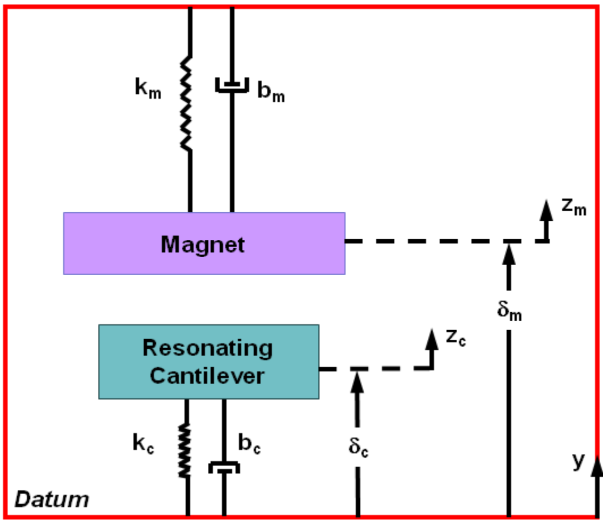

Figure 2. Equivalent mechanical model of the system.

The dynamic behavior of the magnet can be obtained by the steady-state solution of the first equation that is already derived in the literature [2]. The cantilevers are basically excited with their release at a certain instance of their motion. Thus, their dynamics is revealed with the transient solution of Equation (2), by assuming that they are released at a vertical distance of z_o.

$$z_c(t) = \frac{z_o e^{-\zeta_c\omega_n t}}{\sqrt{1-\zeta_c^{\,2}}}\left(\zeta_c \sin(\omega_d t) + \sqrt{1-\zeta_c^{\,2}}\cos(\omega_d t)\right) \qquad (3)$$

In the last equation, ζ_c and ω_d correspond to the overall damping ratio and the damped natural frequency of the cantilevers. After obtaining the equations representing the dynamic behavior of the system, the generated voltage from a single cantilever can be obtained as:

$$\varepsilon = -BL_P\dot{z}_c \qquad (4)$$

In this equation, B is the magnetic flux density and L_P is the practical coil length. These terms are derived and investigated in detail in the previous work of Sari *et al.* [2]. By using (3) and (4), the output voltage generated by a single cantilever can be derived as:

$$\varepsilon = BL_P z_o \omega_n \frac{e^{-\zeta_c\omega_n t}}{\sqrt{1-\zeta_c^{\,2}}}\sin(\omega_d t) \qquad (5)$$

The power output can be obtained using the following equation,

$$P = \frac{1}{2}\frac{R_L}{(R_L+R_c)^2}\varepsilon^2 \qquad (6)$$

where R_L and R_c are the load and coil resistances, respectively. After making necessary substitutions, the power terms can be defined in expanded form as,

$$P = \frac{1}{2}\frac{R_L}{(R_L+R_c)^2}\left(BL_P z_o \omega_n \frac{e^{-\zeta_c\omega_n t}}{\sqrt{1-\zeta_c^{\,2}}}\sin(\omega_d t)\right)^2 \qquad (7)$$

The power and voltage terms defined above are optimized using a Pattern Search algorithm in Matlab® to have maximum output from the proposed device. The optimized generator parameters are tabulated in Table 1. According to the optimized results, a maximum voltage of 0.67 mV and a power of 0.33 nW are estimated to be obtained from a single cantilever of the generator. Figure 3 shows the simulated absolute positions of the cantilevers and the magnet obtained using the parameters of Table 1.

Table 1: Optimized parameters of the generator.

Input vibration frequency	70–150 Hz
Diaphragm natural frequency	113 Hz
Input displacement	0.44–2 mm
Device dimensions	8.5 x 7 x 2.5 mm^3
Magnetic flux density	0.19 Tesla
Magnet size	3.8x3.8x1.5 mm^3
Total number of cantilevers	20
Cantilevers natural frequency	2 kHz
Cantilever size	1000 x 430 x 15 μm^3
Magnetic actuation area	430 x 225 x 9 μm^3
Nickel thickness	9 μm
Coil width	20 μm
Release height of the cantilevers	200 μm
Practical coil length	1.4 mm
Number of coil turns	6
Collected energy in 1s (20 cantilevers)	610 pJ (30.5 pJ/cantilever)
Peak power output (20 cantilevers)	6.6 nW (0.33 nW/cantilever)
Peak voltage output (20 cantilevers)	13.5 mV (0.67 mV/cantilever)

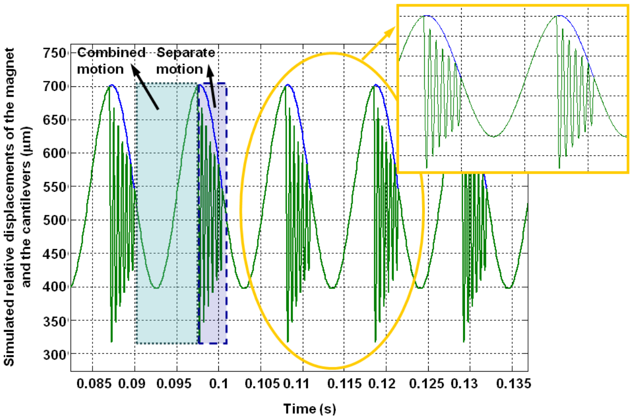

Figure 3: Simulated relative positions of the magnet and the cantilevers.

The system has three different dynamics: (1) cantilever, (2) magnet-diaphragm, and (3) combined motion of the cantilevers and magnet-diaphragm. During the simulation, the model is switched between these three dynamic modes, by continuously checking the effective conditions at each sample time step. The shaded area on the left (bordered by the dotted line) shows the combined low–frequency motion of the cantilevers and the magnet, whereas the shaded area on the right (bordered by the long dashed line) shows the separate motion of the cantilevers (high frequency plot) and the magnet (low frequency plot). The generated voltage from a single cantilever is also plotted in Figure 4, which has an exponentially decaying out form similar to the motion of the cantilevers. It can be seen that voltage generation is realized during the high frequency oscillatory motion of the cantilevers after their release.

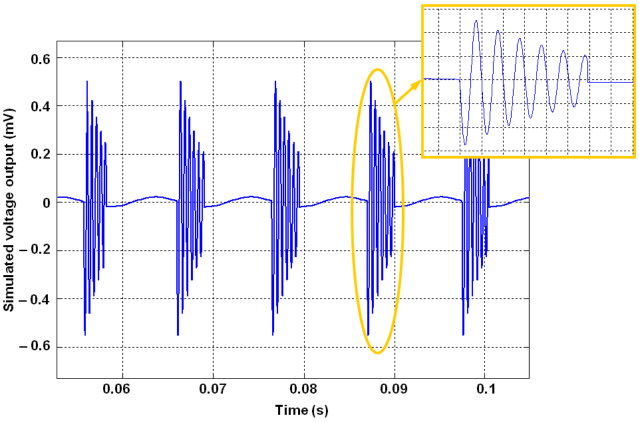

Figure 4: Simulated voltage output from a single cantilever.

IMPLEMENTATION AND TEST RESULTS

Fabrication of the micro generator requires 5 masks and is explained in detail in [4]. Parylene C is used as the structural material for the cantilevers and the diaphragm as it allows much larger deflections before mechanic failure compared to silicon [5].

Figure 5 shows the fabricated prototype placed on the shaker table (upper left) and the assembled prototype with its subcomponents prepared for testing (bottom right). The tests are carried out by sweeping the frequency from 70 to 150 Hz. Table 2 shows the test results indicating that the estimated and measured values for a single cantilever are in good agreement. The main source of minor deviation is due to the error in the estimation of the magnetic flux density, which is a complicated parameter for accurate calculation. Figure 6 shows the simulated and measured output voltages plotted on the same set of axis. The plot on the upper-left hand side is a zoomed out view of the generated voltage and it shows that the cantilevers are continuously caught and released, proving the realization of the up-conversion mechanism. The plots on the right hand side are close-up views of the generated voltage, and they show that the simulation and test results are in close agreement. The bottom plot indicates the catch and release points together with the excitation and up-converted frequencies.

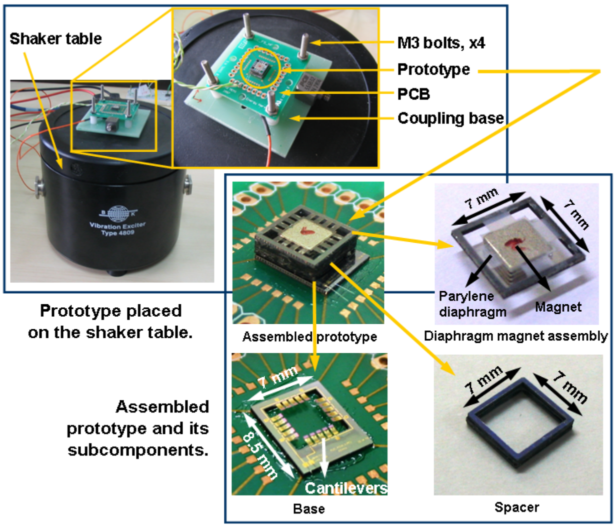

Figure 5: Fabricated prototype prepared for testing.

Table 2: Comparison of the simulation and the test results of the frequency up-conversion (FU) design.

	Simulation	**Test**
Input vibration frequency	70–150 Hz	70–150 Hz
Input displacement	0.44–2 mm	0.44–2 mm
Diaphragm natural frequency	113 Hz	113 Hz
Cantilevers natural frequency	2 kHz	2 kHz
Magnet size (mm^3)	3.8x3.8x1.5	3.8x3.8x1.5
Release height of the cantilevers	200 µm	200 µm
Damping ratio of the cantilevers	0.02	0.02
Coil resistance	160 Ω	150 Ω
Energy in 1 s (single cantilever)	30.5 pJ	20 pJ
Peak power (single cantilever)	0.33 nW	0.25 nW
Peak voltage (single cantilever)	0.67 mV	0.57 mV

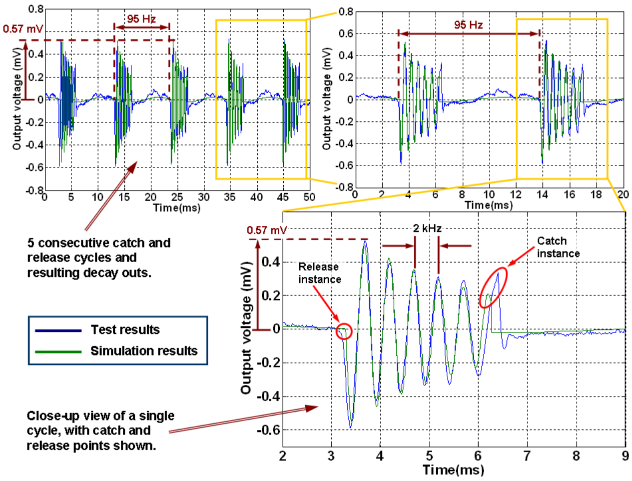

Figure 6: Estimated and measured voltages.

In order to prove the effectiveness of the proposed generator, a same-sized traditional large magnet-coil (MC) type generator has also been fabricated and tested for performance. MC type generator is one of the most popular traditional EM energy scavengers and it has been extensively investigated in the literature [1]. Figure 7 shows the fabricated traditional generator. The base shown on the lower left hand corner is stationary whereas the magnet-diaphragm assembly shown on the upper right hand side is moveable to induce voltage at the terminals of the coil. Table 3 compares the performance of the FU and MC designs.

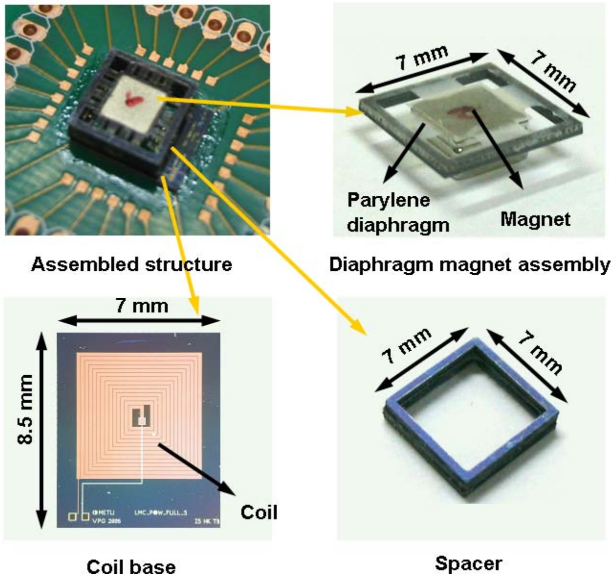

Figure 7: The traditional magnet-coil design fabricated for comparison with the proposed design.

Table 3: Performance comparison of the frequency up-conversion (FU) and the magnet-coil (MC) designs.

	MC design	FU design (single cant.)	FU design (20 cants.)
Size (mm^3)	8.5x7x2.5	8.5x7x2.5	8.5x7x2.5
Effective frequency	91-99 Hz	70-150 Hz	70-150 Hz
Excitation frequency	95 Hz	95 Hz	95 Hz
Magnet size (mm^3)	3.8x3.8x1.5	3.8x3.8x1.5	3.8x3.8x1.5
Coil resistance	257 Ω	150 Ω	3 kΩ
Energy (in 1s)	30 pJ	20 pJ	400 pJ
Maximum power	0.04 nW	0.25 nW	5 nW
Maximum voltage	0.30 mV	0.57 mV	11.4 mV

As Table 3 shows, a single cantilever of the FU design can generate about 2 times the voltage and 6 times the power that the MC design can provide. These values are multiplied by 20 when the overall performances of the generators are compared. The generated outputs from the generators have different wave forms; sinusoidal for the MC design and decaying out for the FU design. Thus, it is more meaningful to compare the generated energies in a certain amount of time. Measurements show that a single cantilever of the FU design can collect about 0.7 times the energy that the MC design can do. However, when the overall performance of the 20 cantilevers is considered this value goes up to 13.

CONCLUSIONS

In this paper, an EM energy generator that up-converts low frequency environmental vibrations to a higher frequency is presented. The micro scale implementation of this design has been firstly shown here and the concept is proven to work in micro scale with actual test results for the first time. It has been shown that a voltage and power output of 0.57 mV and 0.25 nW can be obtained from a single cantilever of the micro-scale design, respectively. The aim of this study is to show that the proposed generator concept works in micro scale and is more efficient compared to a same sized traditional micro generator operating under the same conditions. For this purpose, the device parameters are optimized in a conservative manner for the verification of the concept. Indeed, it has been shown that the proposed generator performs much better than a traditional MC design. However, it is also possible to further improve the generated voltage and power by decreasing the coil width to increase the coil turns or by increasing the number of cantilevers. For example, in this design, a coil width of 20 µm has been used and it can be decreased to 2 µm to increase the generated outputs. Initial calculations show that this improvement leads to a 6.5 fold increase in the voltage and power output levels. With further improvements in the design parameters, it is possible to improve the performance of the proposed generator.

ACKNOWLEDGMENTS

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