7th Int. Workshop on Micro and Nanotechnology for Power Generation and
Energy Conversion Applications (PowerMEMS 2007), Freiburg, 2007, pp. 141-144.

OPTIMAL DESIGN OF VIBRATION-DRIVEN MICRO ELECTRET GENERATOR FOR ENERGY HARVESTING

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Abstract: In the present study, we have developed a complete model of the vibration-driven micro electret power generator and made an optimal design for maximum power output. Response of the present generator model is in agreement with the prediction with the VDRG model when the damping coefficient is provided with the present model. It is found that the optimum design condition is dependent on the magnitude of the seismic mass amplitude versus its traveling length limit.

Key Words: energy harvesting, electret, power generator, simulation, VDRG model

1. INTRODUCTION

Energy harvesting with MEMS generators from environmental vibration attracts much attention, because such pertetuum energy supply is useful for low-power electronic devices such as RFID and mechanical transducers [1]. Since the frequency range of the vibration existing in the environment remains as low as tens of Hz, electret generators should have higher performance than electromagnetic ones [2, 3].

Figure 1 shows the vibration-driven micro electret generator designed in our previous study [3]. When in-plane vibration is imposed, amount of induced charges on the counter electrode is changed due to the variation in the overlapping area, and this produces alternative electric current in the external circuit.

We recently discover that CYTOP, which is MEMS-friendly amorphous perfluoro-polymer, can sustain a very-high surface charge density as a stable electret material [3]. We have also demonstrated that up to 0.28 mW power can be obtained with a prototype device at an oscillation frequency as low as 20Hz. The mechanical link between the seismic mass and the frame should have low spring constant for resonance to the environmental vibration and allow large in-plane oscillation amplitude for large power output. In our generators, parylene high-aspect-ratio springs [4] are employed.

However, the oscillation amplitude and thus the power output are dependent not only on the design of the mechanical parts, but also the electrostatic reactive force, which is function of various design parameters including the electrode arrangements and the external electric circuits.

The objective of the present study is to develop a numerical simulation scheme based on the electromechanical model of the generator, and to propose an optimal design method of the electret power generator.

2. ELECTROMECHANICAL MODEL

Figure 2 shows the electrical model used in the present study, where σ, d, g and C_p are respectively the surface charge density, thickness of the electret film, the gap between the electret and the counter electrode, and the parasitic capacitance of the system. Interdigital electrodes consist of base/counter electrodes and guard electrodes. One-dimensional electric field is assumed between the electrodes. External load is assumed to be a pure resistance R.

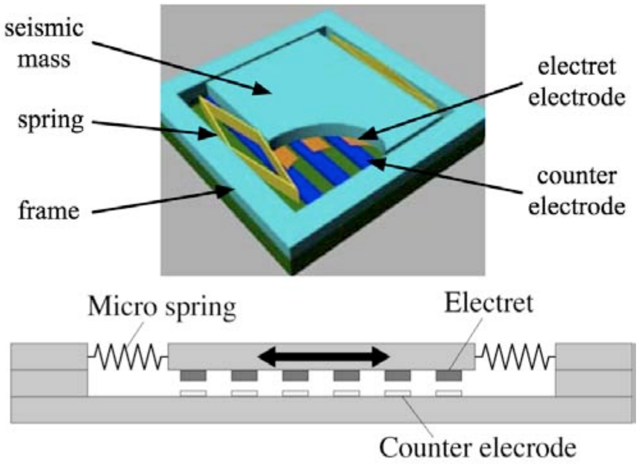

Fig. 1. Schematic of vibration-driven micro electret power generator.

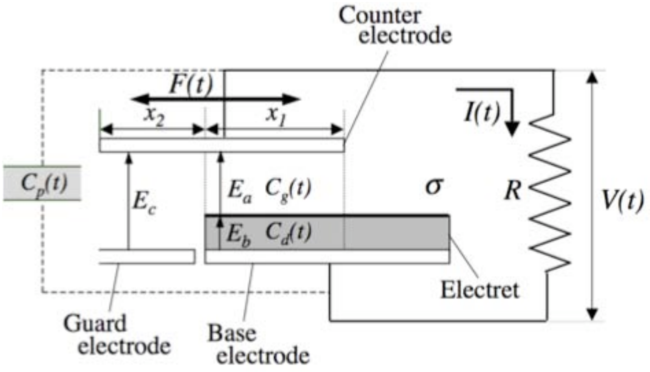

Fig. 2. Computational model of electret generator.

By applying Gauss' and Kirchhoff laws as well as the equation for conservation of charges, four equations for the electric fields between the electrodes and the induction current are derived (see Tada [5] and Tsutsumino et al. [6] for details). By solving the first order differential equation based on the set of equations, we can get the output voltage $V(t)$. In order to obtain the electrostatic reactive force, we employ the energy conservation equation,

$$\frac{dE_S}{dt}+\left(\frac{V^2}{R}+C_P V\frac{dV}{dt}\right)+F_e(t)\frac{dz}{dt}=0\,, \qquad (1)$$

where E_S, $F_e(t)$, and $z(t)$ are respectively the electrostatic potential, the electrostatic force in the horizontal direction, and the displacement of the seismic mass.

The equation motion of the seismic mass, of which oscillation is induced by the environmental sinusoidal vibration $y(t)$ is,

$$m\ddot{z}+D_m\dot{z}+kz+F_e=-m\omega^2 y_0\cos\omega t\,, \qquad (2)$$

where m, D_m, k, y_0, and ω are respectively mass of the seismic part, damping coefficient that represents the parasitic damping of the mechanical system, the spring constant, the amplitude of the external vibration and its angular frequency. This equation of motion is solved in conjunction with the equation for the electric part mentioned above. Amplitude of the seismic mass z_0 is determined through this coupled simulation.

In our previous study, Tsutsumino et al. [6] found that large electrostatic force acts in the direction to which the overlapping area increase, which will deteriorate the performance of the generators. They propose a two-phase arrangement of the electrodes, by which two separate generators with a 180º phase difference are integrated on a single seismic mass. With this configuration, the magnitude of horizontal electrostatic force is drastically decreased, and $F_e(t)$ is proportional to the velocity of the seismic mass, which is in accordance with the velocity damped resonant generator (VDRG) model [7].

3. OPTIMAL DESIGN PROCEDURE

For optimal design of generators, the maximum power output or the maximum efficiency under given operation condition is the possible cost function. In the present study, we have chosen the maximum power output as the cost function, because power output at the maximum efficiency could be infinitely small.

In this section, power output and efficiency of the generator are discussed based on the VDRG model. With the VDRG model, the electrostatic reactive force $F_e(t)$ is assumed to be

$$F_e(t)\approx D_e\dot{z}\,, \qquad (3)$$

where D_e is the 'electrostatic' damping coefficient. In our preliminary simulation, we found that D_e is almost constant for different external amplitudes.

As discussed by Mitcheson et al. [7], operation condition of the generators can be divided into two regimes when we have a limitation of the traveling length z_{lim} for the seismic mass, i.e., $z_0<z_{lim}$ or $z_0=z_{lim}$. In the former case, the amplitude is smaller than the limit, so that the output power is maximized for $D_e= D_m$. In this case, the efficiency η calculated with

$$\eta=\frac{1}{1+D_m/D_e} \qquad (4)$$

becomes 50%. On the other hand, when the amplitude of the seismic mass becomes larger, we have to increase D_e to ensure $z_0=z_{lim}$. In this case, D_e is determined by

$$D_e=\frac{y_0\sqrt{km}}{z_{\text{lim}}}-D_m\,, \qquad (5)$$

and the efficiency η is larger than 50%. However, the parameters are out of the 'global' optimal condition for the maximum power.

In the present study, we optimize the gap g and the external load R for given external amplitude y_0 and the angular frequency ω, which represent different operating conditions. When $z_0<z_{lim}$, we employ a steepest descent method in the 2-D design space of the gap and the load to maximize the power. When $z_0=z_{lim}$, we find an

Table 1. Parameters of the simulation.

Frequency: ω	20 Hz
Mass: m	1 g
Quality factor: Q	15
Width of seismic mass: W	20 mm
Length of seismic mass: b	20 mm
Width of electret: w	150 μm
Thickness of electret: d	20 μm
Parasitic capacitance: C_p	4 pF
Surface voltage: V_s	-600 V
Limit of the traveling distance: z_{lim}	1 mm (2 mm$_{\text{p-p}}$)
External oscillation amplitude: y_0	30-500 μm

initial value for the gap and the load that satisfy $z_0=z_{lim}$ with an external amplitude y_0 and then find the maximum power by using a secant method.

4. SIMULATION RESULTS

Table 1 summarizes parameters of the present simulation. The mechanical damping coefficient is determined by the quality factor of parylene high-aspect-ratio spring (Q=15) [4]. Figure 3 shows the computational results of the amplitude of the seismic mass z_0 for different external oscillation amplitudes y_0. It is found that z_0 is increased linearly up to y_0~145 μm. When y_0 becomes larger, z_0 reaches its limit and stays at z_{lim}.

Figure 4 shows the maximum output power and efficiency versus the external oscillation amplitude y_0. When y_0<145 μm, the power is proportional to y_0^2, and the efficiency is 50 %. This can be explained with the VDRG model [7]. In the VDRG model, the maximum power is

$$P_{\max} = \frac{1}{2} y_0 z_0 m\omega^3 . \tag{6}$$

Since z_0 is proportional to y_0 for y_0<145 μm, the output power should be proportional to y_0^2. In addition, as described in Chap. 3, the efficiency in this regime is 50%.

In Fig. 4, performance of the VDRG model is also shown. For the VDRG model, the 'electrostatic' damping coefficient D_e for the maximum power is determined with D_m as discussed in Chap 3. It is found that prediction with the VDRG model is in good agreement with the simulation results of the present model.

On the other hand, when y_0>150 μm (z_0 reaches its limit), the maximum power becomes

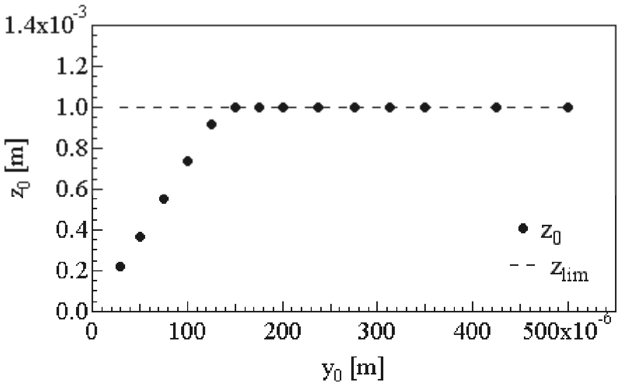

Fig. 3 Amplitude of the seismic mass versus the external oscillation amplitude.

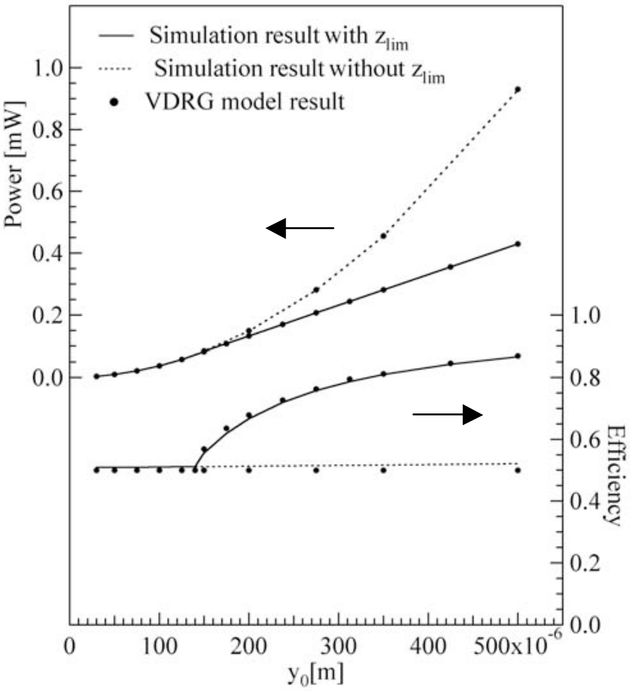

Fig. 4. Maximum power versus the external oscillation amplitude with and without the limitation of the traveling distance.

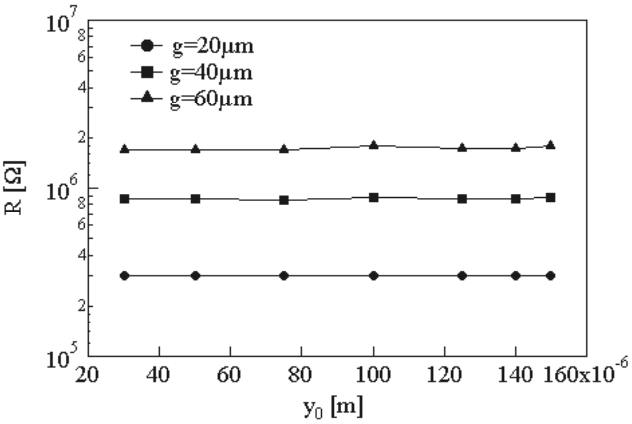

Fig. 5. Optimum load versus external oscillation amplitude for $z_0 < z_{lim}$.

proportional to y_0, since z_0 is constant at z_{lim}. In this case, the efficiency is increased with y_0. This is because $D_e > D_m$ as described in the previous chapter.

For y_0=500 μm, the maximum power and the efficiency are respectively 0.43 mW and 0.86. If there is no limitation for the traveling length, the maximum power and the efficiency would be 0.93mW and 0.5, respectively. In the following, we investigate the optimum parameters that give the maximum power of the generator.

Figure 5 shows the gap *g* and the load *R* optimized for y_0<145 μm (i.e., $z_0 < z_{lim}$). In this case, there are many pairs of *g* and *R*; for any value of *g* (at least for g<60 μm), there is a value of *R* that satisfy $D_e = D_m$. The optimum load is constant for different y_0. This result is very important for the design of the micro generator, because the external resistance can be fixed at the optimum value as far as the amplitude of the seismic mass is smaller than the traveling length limit.

When z_0 reaches its limit, we have unique pairs of the optimum gap and load for each value of y_0. Figure 6 shows the optimum load and gap versus the external amplitude y_0. Both the optimum gap and load are decreased with increasing y_0, since D_e should be increased with constant z_0. However, for relatively large change in y_0, somewhat small variation of the optimum load and gap is sufficient to maintain the optimum design point.

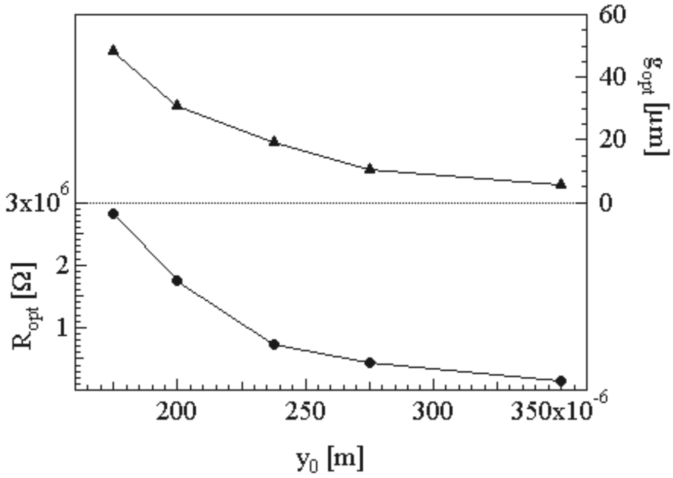

Fig. 6. Optimum gap and load versus external oscillation amplitude for $z_0 = z_{lim}$.

5. CONCLUSION

In the present study, a complete model of electret power generator has been successfully developed and an optimization method for the generator design have been proposed. The following conclusions are derived:

- Response of the present generator model is in agreement with the prediction with the VDRG model when the damping coefficient is provided with the present model.
- When the amplitude of the seismic mass is smaller than the limit of the traveling length, multiple optimal points for the gap and the load exist for the maximum power output.
- When the amplitude becomes the same as its limit, both the optimum gap and load are uniquely determined, and decreased with increasing the amplitude of the external oscillation.

This work is partially supported through Strategic Informetion and Communications R&D Promotion Programme (SCOPE) of JAPAN.

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