A New Technique of Equivalent Circuit Modeling for Micro Electret Vibration Power Generators

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Abstract—We present a new technique of equivalent circuit modeling technique for micro electret vibration power generators. It characterizes the electro-mechanical behavior of the power generators, and expresses as an equivalent circuit model. We explain the technique and implement the equivalent circuit model to a circuit simulator, called LTSPICE. Our experimental results demonstrate that our equivalent circuit model is very accurate. They also reveal that our technique has the capability of dealing with the practical industrial circuit design and circuit analysis.

Keywords—energy harvesting, electret vibration power generator, power output, electro-mechanical behavior, equivalent circuit model, LTSPICE.

I. INTRODUCTION

RECENTLY, energy harvesting is becoming very important as a new power generation system. It captures the energy sources in our surrounding, and converts in electric energy. Among various prototypes for energy harvesting, vibration-driven micro power generation attracts much attention. Vibration-driven micro power generators capture environmental vibration energy, and generate micro electric energy for low-power electronics.

Moreover they are able to provide a source of energy without long term maintenance in the state of being separated from the system power supply, and have potential to replace secondary batteries used for the wireless monitoring system, such as automotives sensor and health monitoring. Since the vibration frequency is below 100Hz, in particular electrostatic vibration power generators using electret dielectric materials have advantages of higher power output than other energy conversion principles [4], [6]-[10].

In this paper, we focus on an electrostatic vibration power generator (micro electret vibration power generator) using an electret dielectric material. The electret is a dielectric material based on CYTOP [4], [6]-[10], which has a quasi-permanent excess electric charge (surface charge). The micro electret vibration power generator consists of a vibration generating

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mechanism and a power generating mechanism. The former transmits the external environmental vibration energy to the vibrator inside the generator. The latter captures the charge transfer on the vibrator which is induced by the electrostatic field formed due to the electret, and converts into the power.

The vibrator is composed of a combination of a counter electrode and a weight. In the micro electret vibration power generator, the electrostatic charge on the counter electrode is provoked by the electrostatic field formed due to the electret (electrostatic induction). The external environmental vibration is transmitted to the vibrator inside the generator, and causes changes in the area of overlap capacitance between the counter electrode and the electret and. It results in changes in the electrostatic charge stored on the overlap capacitance, and produces alternating currents for an external electric circuit connected in the generator. The vibration is absorbed by a spring which is connected into the weight. When the frequency of the vibration is equal to the resonant frequency of the weight and spring, the generator become a resonant state and has a maximum power output [4]-[5], [7], [9]-[10].

We briefly review previous main research activities with respect to the circuit simulations for micro electret vibration power generator. In the researches of [2]-[4], [7], [9], the vibration generating mechanism is modeled as an equation of motion, and the power generating mechanism is modeled as a differential equation based on Gauss's and Kirchhoff's law. This combination of equations is solved numerically by using a general-purpose analysis tool such as Matlab [12]. However, in the circuit analysis by the general-purpose analysis tool, it is not able to utilize accurate SPICE models of such circuit parts as transistors, diodes, and LEDs, which are used in the application circuits of the power generator. Therefore, it is not suitable for practical industrial circuit design and analysis. Furthermore, in [1], the equivalent circuit model which expresses the behavior of power generator as a simple analytical function has been presented. However this model is not accurate, and is insufficient for the practical industrial circuit design.

On the other hand, such MEMS simulators as MemsOne [13], SUGAR [15], and NODA [14] have been developed. However they are device simulators and the purpose of them are to analyze the behavior and characteristics inside MEMS devices. Therefore, they are not suitable for circuit designs.

Under the above mentioned background, we propose a new technique of equivalent circuit modeling for micro electret vibration power generators. It comprises two equivalent circuit

models, which correspond to the vibration generating mechanism and the power generating mechanism. Moreover it enables to analyze the behavior and characteristics of the power generator and application circuits by using such circuit simulator as SPICE.

We implemented our technique to a circuit simulator called LTSPICE [11]. In our experiments, we applied the technique to the circuit simulations of a power output circuit and a LED driver circuit. We ran them on LTSPICE, and compare with circuit measurement results under the same conditions and settings. The results from our simulation are in accord with the circuit measurement results. This implies that our modeling technique produces correct results.

In the next section, we explain about a micro electret vibration power generator, and describe its structure and mechanism. Section III derives our equivalent circuit model of the power generator, and implements it to LTSPICE. Section IV describes our experiments and compares the results. We conclude the paper in Section VI.

NOMENCLATURE

M : mass of the vibrator (combination of the weight and the counter electrode) [Kg/m]

k : spring coefficient [N/m]

f_0 : natural (resonant) frequency) [Hz]

ω_0 : natural (resonant) angular frequency [rad/sec]

f : vibration frequency [Hz]

ω : vibration angular frequency [rad/sec]

l : Length of the electret [m]

a : Width of the electret [m]

b : Distance between adjacent electrets [m] ($b = a$)

d : Thickness of the electret [m]

g : Gap distance of a pair of the counter electrode and electret [m]

t : Time domain [sec]

$x(t)$: Displacement of the vibrator inside the power generator [m].

x_0 : Amplitude of the internal vibrator [m]

C_g : Gap capacitance of a pair of the electret and counter electrode [F/m^2]

C_d : Capacitance of the electret [F/m^2]

C_t : Serial capacitance of the C_g and C_g [F/m^2]

N : Number of convex pairs between the counter electrode and electrets [-]

S : Area of the electret [m^2] ($S = l \times a$)

ε_0 : Vacuum permittivity [F/m]

ε_1 : Relative permittivity of air [-]

ε_2 : Relative permittivity of the electret [-] (Dielectric)

V_s : Surface potential of the electret [V]

Q : Quality factor [-]

$V_{gen}(t)$: Potential between the counter electrode and the base electrode [V]

$Q_{gen}(t)$: The amount of electric charge generated inside the power generator [C]

$I_{gen}(t)$: Current generated inside the power generator [A]

$C_{gen}(x)$: Overlap capacitance between the base electrode and the counter electrode [F].

$C_{gen(min)}$: Minimum value of the $C_{gen}(x)$ [F]

$C_{gen(max)}$: Maximum value of the $C_{gen}(x)$ [F]

C_p : Parasitic capacitance inside the power generator [F]

$V_{mnt}(t)$: Monitoring voltage of the power generator [V]

$V_{out}(t)$: Output voltage of the power generator [V]

R_{mnt} : External resistance for the voltage monitoring [Ohm]

R_{load} : External load resistance [Ohm]

L_{eqv} : Inductance of the LCR equivalent circuit [H]

R_{eqv} : Resistance of the LCR equivalent circuit [Ohm]

C_{eqv} : Capacitance of the LCR equivalent circuit [F]

$V_{eqv}(t)$: Output voltage of the LCR equivalent circuit [V]

$q_{eqv}(t)$: The amount of electric charge conserved in the LCR equivalent circuit [C]

y_0 : Amplitude of the external vibration [m]

D_{meca} : Mechanical damping coefficent [N·sec/m]

D_{elec} : Electrostatic damping coefficient [N·sec/m]

pp(+): plus terminal of power generator
nn(−): minus terminal of power generator
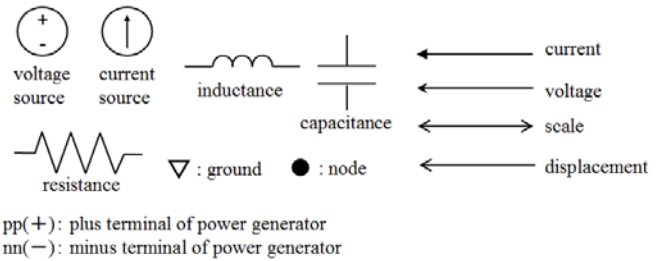
II. STRUCTURE OF MICRO ELECTRET VIBRATION POWER GENERATOR

Figure 1 depicts the cross-section view from the side of the micro electret vibration power generator. This power generator consists of a plastic case in which it is stored itself, a vibrator, a spring, and a base electrode on which many electrets are fixed convexly. The base electrode is fixed on the bottom of plastic case. Moreover the vibrator is composed of a weight and a counter electrode. The external environmental vibration energy causes the displacement of the vibrator in the horizontal direction (x-axis direction). The spring which is connected to the weight absorbs the energy. The counter electrode and the base electrode have a teeth-shaped structure respectively, and they are located on opposite sides through the electrets. The displacement of the vibrator induces changes in the overlap area of capacitance between the counter electrode and the base electrode. As a result, the alternating currents are produced by the electrostatic induction of the electrets of the base electrode. And they are supplied for an external electric circuit connected in the power generator.

In the initial condition which the vibration is not occurred (t=0), The initial displacement is defined as the following: x=$x(t)$=$x(0)$=0. The counter electrode, the base electrode, and the electrets have a same length (l) in the depth direction toward this paper respectively.

Figure 2 depicts the cross-section view from the above of the micro electret vibration power generator. The vibrator is subject to mechanical frictional force (D_{meca}). Moreover it is also subject to the electrostatic friction (D_{elec}) due to the electrostatic

attraction between the counter electrode and the base electrode. Our model considers these frictional forces.

Next section describes our modeling technique. It derives our equivalent circuit models for the vibration generating mechanism and the power generating mechanism. In the following discussion of this paper, we assume that the direction of vibration is horizontal. In other words, the direction of vibration is perpendicular to the force of gravity. Furthermore, it assumes that the plastic case in which the vibrator is stored itself has a sufficient size. Therefore we do not impose a restriction on the range of values of the displacement of the vibrator.
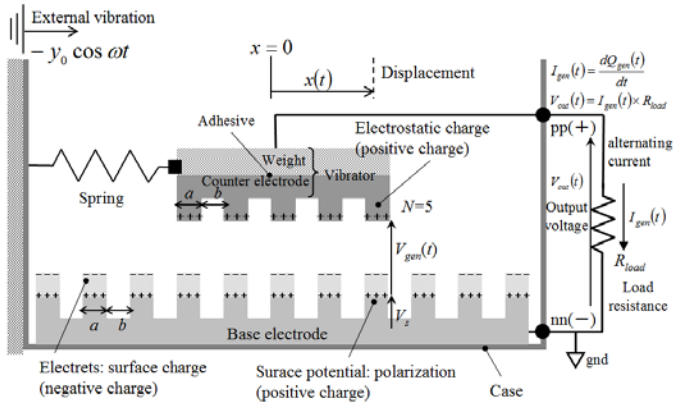
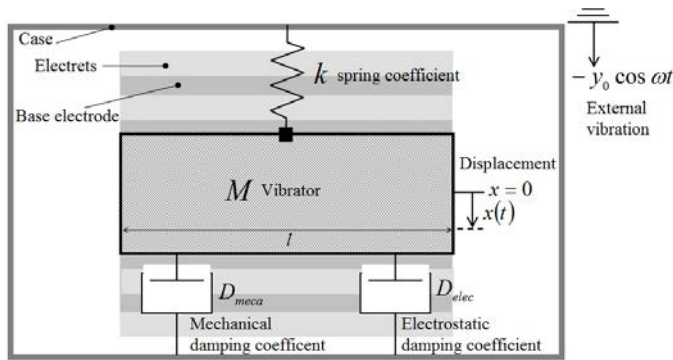Fig. 1: Cross-section view from the side. An example of case: $N=5$.


Fig. 2: Cross-section view from the above.

III. OUR EQUIVALENT CIRCUIT MODEL

### A. Modeling of Power Generating Mechanism

In the mechanism of power generating, the external environmental vibration causes changes in the area of overlap capacitance between the counter electrode and the electret. It results in changes in the electrostatic charge stored on the overlap capacitance, and produces alternating currents for an external electric circuit connected in the generator. In this section, we derive an equivalent circuit model for the power generating mechanism. For the sake of simplicity, we assume that the width of the electret (a) is equal to the distance between adjacent electrets (b). As mentioned in Section I, we assume also that the displacement of vibrator has no upper and lower limits.

Figure 3 depicts a condition under which the (electrostatic) overlap capacitance between the counter electrode and the base electrode become maximum and minimum. The overlap area becomes maximum under the condition that the displacement is equal to the integral multiple of ($a + b$) to the positive or negative direction. The resulting capacitance takes the maximum value. Furthermore, under the condition that the displacement is shifted by the length a from the above described position, the capacitance takes the minimum value. Thus, the change of overlap capacitance has a periodicity due to the sliding of the vibrator.
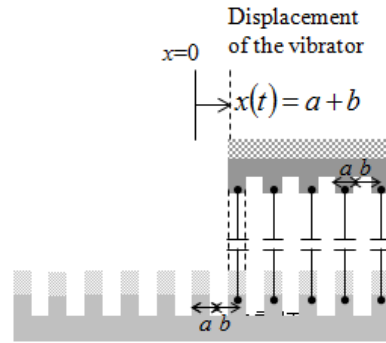
(a) Example of when the overlap capacitance becomes maximum
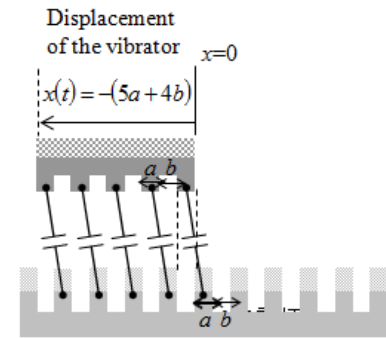
(b) Example of when the overlap capacitance becomes minimum

Fig. 3: Overlap capacitance between the counter electrode and base electrode.

Next, as depicted in Fig. 4, we deal with a convex pair of teeth-shaped structure between the counter electrode and base electrode, which are located on opposite sides through an electret. As explained below, we derive a overlap capacitance model for this convex pair.

The gap capacitance per unit area (C_g) of the pair of the counter electrode and electret is expressed as Eq. (3-1). The electret capacitance per unit area (C_d) is expressed as Eq. (3-2). The resultant serial capacitance (C_t) that is composed of these two capacitances (C_g and C_d) is expressed as Eq. (3-3). It corresponds to the capacitance per unit area of the convex pair between the counter electrode and the base electrode.

$$C_g = \frac{\varepsilon_1 \varepsilon_0}{g} \tag{3-1}$$

$$C_d = \frac{\varepsilon_2 \varepsilon_0}{g} \tag{3-2}$$

$$C_t = \frac{C_g \times C_d}{C_g \times C_d} = \frac{\varepsilon_1 \varepsilon_0}{g + \dfrac{\varepsilon_1}{\varepsilon_2} d} \tag{3-3}$$
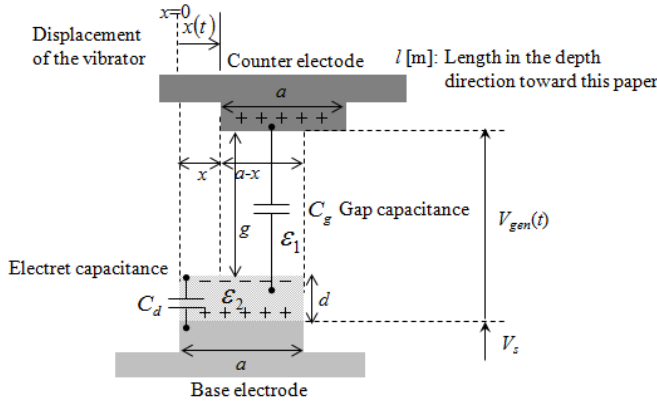

Fig. 4 Capacitance model of the convex pair.

The overlap length of the convex pair is $(a - x)$ as depicted in Fig. 4. Therefore the maximum $(C_{gen(max)})$ and minimum $(C_{gen(min)})$ of overlap capacitance of the pair are expressed as Eqs. (3-4) and (3-5), respectively.

$$C_{gen(max)} = C_t \times l \times (a - 0) = C_t \times S \tag{3-4}$$

$$C_{gen(min)} == C_t \times l \times (a - a) = 0.0 \approx 1.0e - 18 \tag{3-5}$$

Note that we set up the minimum value of overlap capacitance to the smallest nonzero positive value (1e-18 [F]) in order to ensure the convergence of circuit simulation.

As mentioned above, the change of overlap capacitance has a periodicity of one cycle length $(a + b)$. Therefore, the overlap capacitance $(C_{gen}(x))$ of the convex pair between the counter electrode and the base electrode is a function of the displacement $x(t)$ and expressed as Eq. (3-6) [2]-[3]. Equation (3-7) is obtained by differentiating Eq. (3-6) in the time domain.

$$C_{gen}(x) = \left(\frac{C_{gen(max)} + C_{gen(min)}}{2} \right) + \left(\frac{C_{gen(max)} - C_{gen(min)}}{2} \right) \times \cos\left(\frac{2\pi x}{a+b} \right) \tag{3-6}$$

$$\frac{dC_{gen}(x)}{dx} = -\left(\frac{2\pi}{a+b} \right) \times \left(\frac{C_{gen(max)} - C_{gen(min)}}{2} \right) \times \sin\left(\frac{2\pi x}{a+b} \right) \tag{3-7}$$

Figure 5 depicts an equivalent circuit model of the power generating mechanism, which comprises N sets of overlap capacitances of convex pairs between the counter electrode and the base electrode. Moreover it also comprises a surface potential due to the electrets. Note that the surface potential is expressed as a constant voltage source. The total capacitance of the N sets of overlap capacitances of convex pairs is modeled as an amount of electric charge and is expressed as Eq. (3-8). The current generated inside the power generator (alternating current) is expressed as Eq. (3-9) and is obtained by differentiating Eq. (3-8) in the time domain.
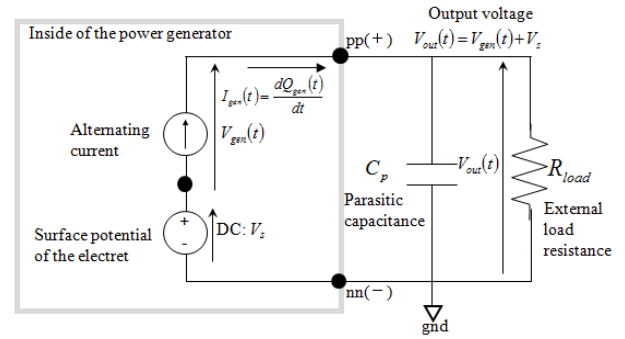

Fig. 5: Equivalent circuit model of power generating mechanism.

$$\left. \begin{array}{l} Q_{gen}(t) = C_{gen}(x(t)) \times V_{gen}(t) \times N \\ V_{gen}(t) = V_{out}(t) - V_s \end{array} \right\} \tag{3-8}$$

$$I_{gen}(t) = \frac{dQ_{gen}(t)}{dt}$$

$$= \left(C_{gen}(x(t)) \times \frac{dV_{gen}(t)}{dt} + \frac{dC_{gen}(x)}{dx} \times \frac{dx(t)}{dt} \times V_{gen}(t) \right) \times N \tag{3-9}$$

B. Modeling of Vibration Generating Mechanism

The resonant frequency (f_0) and resonant angular frequency (ω_0) of the power generator are defined as Eqs. (3-10) and (3-11), respectively. Moreover the relation between the vibration frequency (f) and the vibration angular frequency (ω) is defined as Eq. (3-12) [4].

$$\omega_0 = \sqrt{\frac{k}{M}} \tag{3-10}$$

$$f_0 = \frac{\omega_0}{2\pi} \tag{3-11}$$

$$\omega = 2\pi f \tag{3-12}$$

The equation of motion (vibration equation) of the vibrator is expressed as Eq. (3-13). In particular, the right hand side of this equation corresponds to an external force due to the external environmental vibration energy. The displacement of the vibrator $(x(t))$ inside the power generator is obtained by solving the equation.

$$M \frac{d^2 x}{dt^2} + D_{meca} \frac{dx}{dt} + D_{elec} \frac{dx}{dt} + kx = M\omega^2 y_0 \cos(\omega t) \tag{3-13}$$

where the mechanical damping coefficient (D_{meca}) and the electrostatic damping coefficient (D_{elec}) are expressed as Eqs. (3-14) and (3-15), respectively. [5]

$$D_{meca} = \frac{M\omega_0}{Q} \tag{3-14}$$

$$D_{elec} = D_{meca} \tag{3-15}$$

We rewrite Eq. (3-13) as follows by using Eqs. (3-14) and (3-15). Finally we obtain Eq. (3-16).

$$\frac{d^2x}{dt^2} + 2\frac{\omega_0}{Q}\frac{dx}{dt} + \omega_0^2 x = \omega^2 y_0 \cos(\omega t) \qquad (3\text{-}16)$$

Furthermore, we focus on an analogy between Eqs. (3-16) and (3-17). Since equation (3-17) is equivalent to a LCR serial circuit, equation (3-16) is expressed as an equivalent circuit depicted in Fig. 6. The equivalent circuit is composed of an inductor,(L_{eqv}), a resistor (R_{eqv}), a capacitor (C_{eqv}), and a voltage source ($\omega^2 y_0 \cos(\omega t)$).

$$L_{eqv}\frac{d^2 q_{eqv}}{dt^2} + R_{eqv}\frac{dq_{eqv}}{dt} + \frac{1}{C_{eqv}}q_{eqv} = \omega^2 y_0 \cos(\omega t) \quad (3\text{-}17)$$

The output voltage ($V_{eqv}(t)$) in the capacitor (C_{eqv}) is obtained by analyzing the equivalent circuit depicted in Fig. 6. Moreover the amount of electric charge ($q_{eqv}(t)$) is obtained by calculating Eq. (3-18). Its value corresponds to the displacement $x(t)$ in Eq. (3-13).

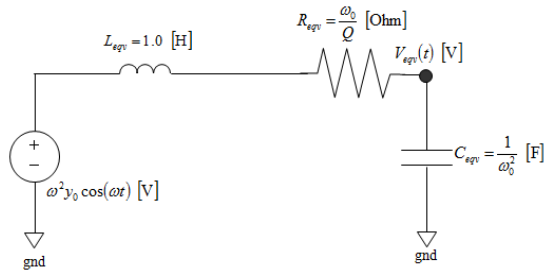$$q_{eqv}(t) = V_{eqv}(t) \times C_{eqv} = V_{eqv}(t) \times \frac{1}{\omega_0^2} \qquad (3\text{-}18)$$

Fig. 6: Equivalent circuit model of vibration generating mechanism.

IV. EXPERIMENTAL RESULTS

A. Implementation into Circuit Simulator

As our experimental verification, by using the above mentioned two equivalent circuit models, we perform a circuit simulation for the micro electret vibration power generator and its external circuits. We implement their equivalent circuit models into a circuit simulator called LTSPICE [11]. The equivalent circuit models of the vibration generating mechanism and the power generating mechanism have the displacement ($x(t)$) which is a variable shared with each other (See Appendix). Therefore, in our circuit simulation, it finds the values of the displacement by simultaneously solving a set of two equivalent circuit models. In the following discussion, for the sake of convenience, we refer to as "our equivalent circuit model".

B. Power output of micro electret vibration power generator

First we consider a test circuit [4] which is composed of a micro electret vibration power generator and an external load resistance as depicted in Fig. 7. The purpose of this test circuit is to evaluate the output power from the generator.

We applied our equivalent circuit model to the test circuit, and ran a circuit simulation in order to obtain the output power. The values of main model parameters are the same as those used in [4]: N=53 [-], L=1.46E-2 [m], a=b=1.50E-4 [m]. d=1.50E-5 [m], g=1.00E-4 [m], ε_0= 8.86E-12 [F/m], ε_1=1.0 [-], ε_2=2.1 [-], V_s=600.0 [V], $C_{gen(min)}$=1.00E-18 [F], $C_{gen(max)}$= 1.81098E-13 [F], C_p=110E-12 [F], R_{load}=8.2E6 [Ohm], R_{mnt}=100e3 [Ohm], M=1.40E-3 [Kg], f_0=21 [Hz], ω_0=2πf_0 [rad/sec], f=21 [Hz], ω=2πf [rad/sec], k=2.211E+1 [N/m], Q=5.23 [-], y_0= 9.60E-5 [m].

Figure 8-(1) depicts changes in the output voltage ($V_{out}(t)$) of the test circuit obtained by our circuit simulation. Moreover the output power is 13.5 [μW]. On the other hand, figure 8-(2) depicts the circuit measurement result of the output voltage described in [4]. Its output power is 12.5 [μW]. Both figures resemble very close to each other. This implies that the circuit simulation using our equivalent circuit model produces correct results.

C. LED driver circuit

Next, as an example of practical industrial circuit, we consider a LED driver circuit described in [4], which is composed of a micro electret vibration power generator, bipolar transistors, resistors, capacitors, and a LED, as depicted in Fig. 9.

We ran a circuit simulation using our equivalent circuit model and the above mentioned model parameter values. As a simulation result, figure 10-(1) depicts changes in the DC output voltage (at node "dc_out" in Fig. 9) after the rectification of the output voltage from the power generator. Since the design parameter values of electronic components such as bipolar transistor, load resistor, and capacitor given in the Fig. 9 are not described in [4], we set typical values used in the industrial circuit design.

On the other hand, figure 10-(2) depicts the circuit measurement result of the voltage described in [4]. Both figures resemble close to each other. This demonstrates that our equivalent circuit model is able to be applied to practical industrial circuit design of micro electret vibration power generators. We consider that the slight difference of voltage between the circuit simulation result and the circuit measurement result is due to the difference in the design parameter setting of each electronic component.

D. External load resistance dependence of output power

Finally we ran a circuit simulation in order to evaluate the external load resistance dependence (R_{load}) of output power in a power generator by using our equivalent circuit model. Figure 11-(1) depicts the circuit simulation result. Note that each curve corresponds to peak-to-peak (p-p) amplitude of internal vibration (x_0) in the vibrator, which is determined by the external vibration (y_0). On the other hand, figure 11-(2) depicts the circuit measurement result and numerical simulation result, which are described in [7]. Both figures resemble to each other. We consider that the difference of output power is due to the difference in the detailed model parameter setting for the power generator.
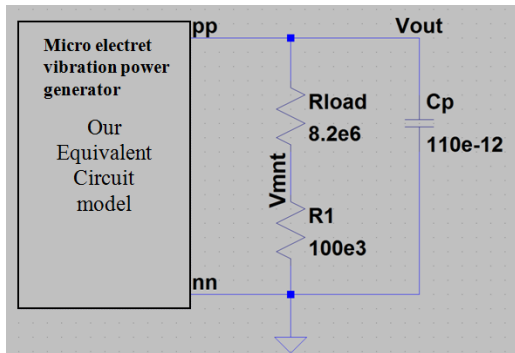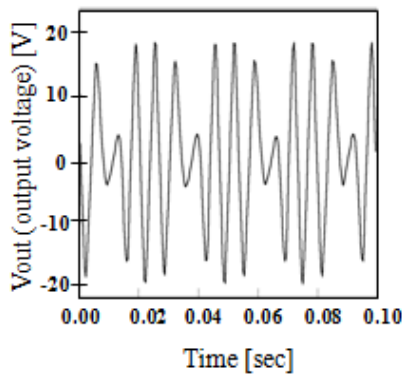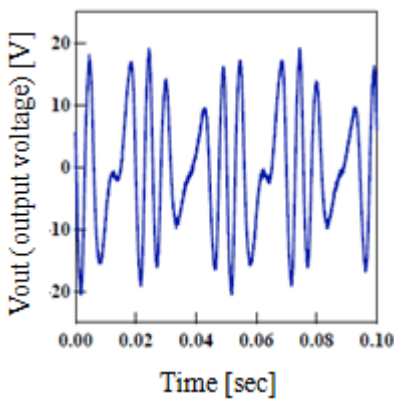
Fig. 7: Test circuit for the evaluation for output power.

(1) Result by our circuit simulation

(2) Result by circuit measurement [4]

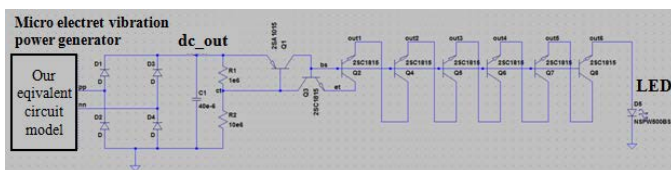Fig. 8: Results obtained by our circuit simulation and circuit measurement result taken from [4].
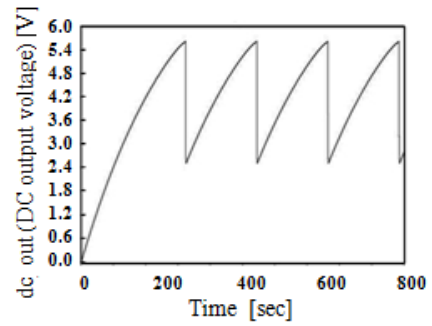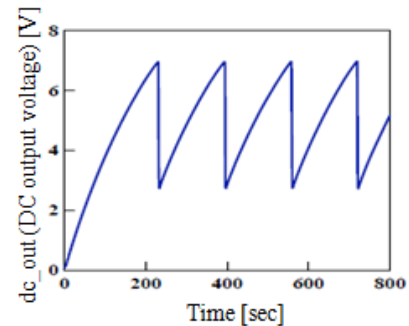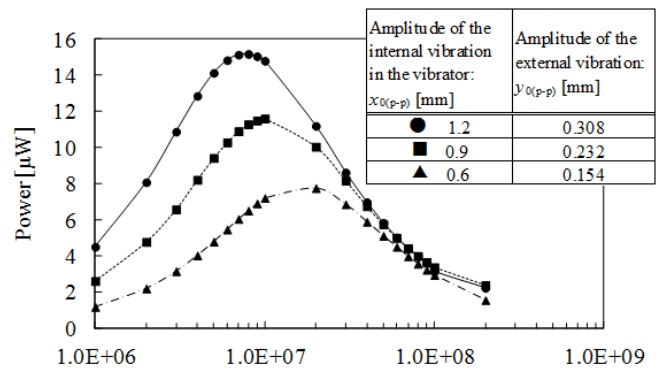

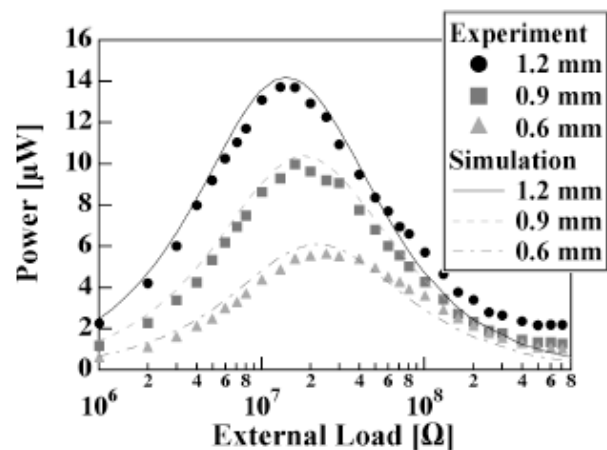Fig. 9: a LED driver circuit.

(1) Result by our circuit simulation

(2) Result by circuit measurement [4]

Fig. 10: Results by our circuit simulation and circuit measurement result taken from [4].

Amplitude of the internal vibration in the vibrator: $x_{0(p-p)}$ [mm]	Amplitude of the external vibration: $y_{0(p-p)}$ [mm]
● 1.2	0.308
■ 0.9	0.232
▲ 0.6	0.154

(1) Result by our circuit simulation

(2) Result by circuit measurement and numerical simulation [7]

Fig. 11: External load resistance dependence of output power.

6

V. Conclusions

We have presented a new technique of equivalent circuit modeling for micro electret vibration power generators. It starts with the modeling of the vibration generating mechanism and power generating mechanism. Moreover it derives an equivalent circuit models. Furthermore, we applied the technique to the circuit simulations of some application circuits of micro electret vibration power generators. Our experimental results demonstrate the validity of our technique. They also revealed that our technique has the capability of dealing with practical industrial circuit design.

In the future work, we continue to improve our equivalent circuit model in order to attain more accurate circuit simulation.

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APPENDIX

An example of implementation of our equivalent circuit model in a circuit simulator, called LTSPICE.
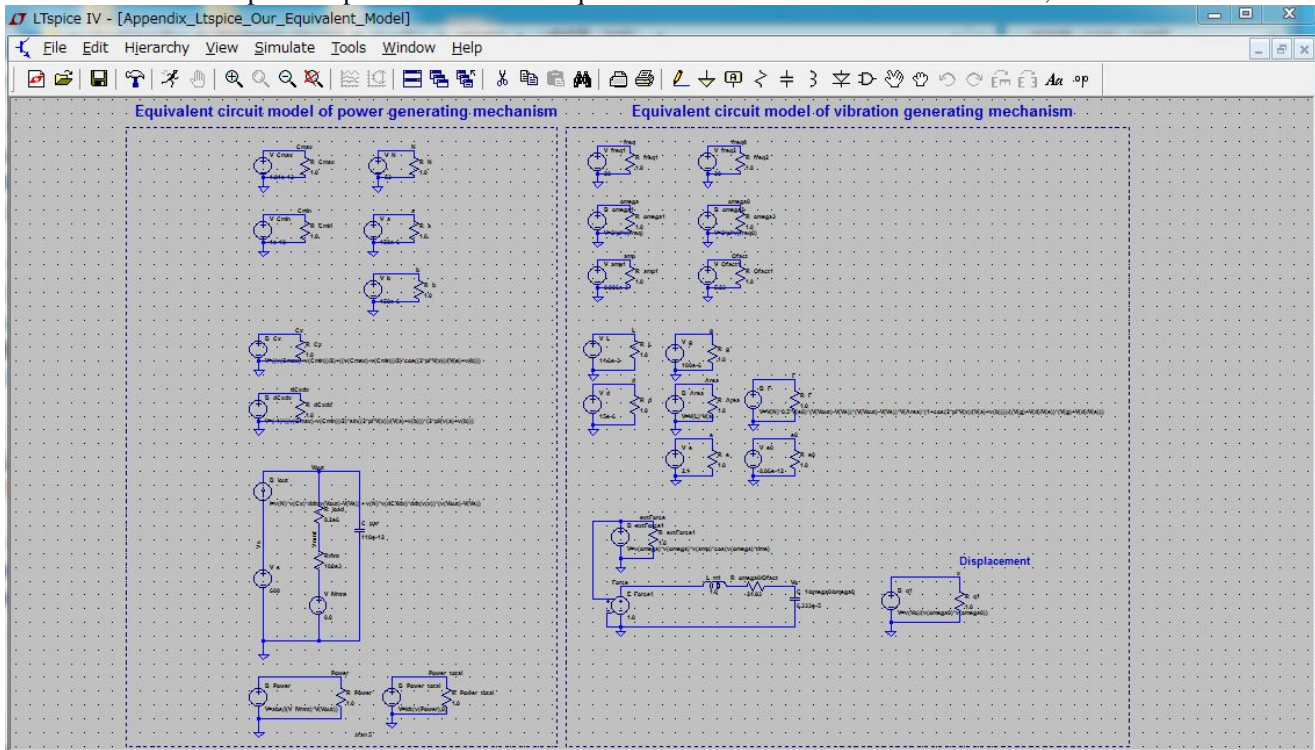

```
*LTSPICE netlist
* Appendix_Ltspice_Our_Equivalent_Model.asc
V_Cmax Cmax 0 1.81e-13
V_Cmin Cmin 0 1e-18
R_Cmax Cmax 0 1.0
R_Cmin Cmin 0 1.0
R_a a 0 1.0
R_b b 0 1.0
V_a a 0 150e-6
V_b b 0 150e-6
V_s Vs 0 600
R_N N 0 1.0
V_N N 0 53
R_Cx Cx 0 1.0
B_Cx                Cx                0
V=((v(Cmax)+v(Cmin))/2)+((v(Cmax)-v(Cmin))/2)*cos((2*pi*V(x))/(V(a)+v
(b)))
B_Iout    Vs    Vout    I=v(N)*v(Cx)*ddt(v(Vout)-V(Vs))    +
v(N)*v(dCXdx)*ddt(v(x))*(v(Vout)-V(Vs))
R_load Vout Vmnt 8.2e6
R_dCxdx dCxdx 0 1.0
B_dCxdx                dCxdx                0
V=(-1)*((v(Cmax)-v(Cmin))/2)*sin((2*pi*V(x))/(V(a)+v(b)))*(2*pi/(v(a)+v(
b)))
C_par Vout 0 110e-12
Rmnt Vmnt N002 100e3
R_freq1 freq 0 1.0
V_freq1 freq 0 20
R_omega1 omega 0 1.0
B_omega1 omega 0 V=2*pi*v(freq)
R_extForce1 extForce 0 1.0
R_amp1 amp 0 1.0
V_amp1 amp 0 0.096e-3
B_extForce1 extForce 0 V=v(omega)*v(omega)*v(amp)*cos(v(omega)*time)
E_Force1 Force 0 extForce 0 1.0

L_m1 Force N001 1.0
R_omega0/Qfact Vo N001 24.03
C_1/omega0/omega0 Vo 0 6.333e-5
* x : Displacement
B_q1 x 0 V=v(Vo)/(v(omega0)*v(omega0))
R_q1 x 0 1.0
R_freq2 freq0 0 1.0
V_freq2 freq0 0 20
R_omega3 omega0 0 1.0
B_omega2 omega0 0 V=2*pi*v(freq0)
R_Qfact1 Qfact 0 1.0
V_Qfact1 Qfact 0 5.23
V_IVmnt N002 0 0.0
B_Power Power 0 V=abs(I(V_IVmnt)*V(Vout))
R_Power Power 0 1.0
B_Power_total Power_total 0 V=idt(v(Power),0)
R_Power_total Power_total 0 1.0
R_L L 0 1.0
V_L L 0 14.6e-3
V_d d 0 15e-6
R_d d 0 1.0
R_g g 0 1.0
V_g g 0 100e-6
R_Area Area 0 1.0
B_Area Area 0 V=V(L)*V(a)
V_e e 0 2.1
R_e e 0 1.0
V_e0 e0 0 8.86e-12
R_e0 e0 0 1.0
R_F F 0 1.0
B_F                F                0
V=V(N)*0.5*V(e0)*(V(Vout)-V(Vs))*(V(Vout)-V(Vs))*V(Area)*(1+cos(2*
pi*V(x)/(V(a)+v(b))))/((V(g)+V(d)/V(e))*(V(g)+V(d)/V(e)))
.tran 5
.end
```