LIQUID-ROTOR ELECTRET MICROPOWER GENERATOR

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ABSTRACT

We present the world's first liquid-rotor electret power generator (LEPG), designed to harvest electricity from low-frequency mechanical vibrations. The device (figure 1) consists of a fixed-charged, Teflon-electret capacitor with an air-filled gap and a liquid droplet that moves by vibration. As the liquid moves into and out of the gap, a net voltage is generated across the capacitor as image charges (induced by the electret) on the two electrodes redistribute according to the position of the droplet. Experimentally, we have proven the feasibility of such a device and our first prototype can generate greater than 30Vpp open-circuit voltage and deliver a power as high as $0.43\mu\text{W}$ to a resistive load (at 28Hz and $R_{\text{load}}=21\text{M}\Omega$). The LEPG may be an economical method to harvest power from vibrational environments to power remote sensing devices.

INTRODUCTION

Portable and remote electronics require power, generally provided by disposable or rechargeable batteries. These sources, however, must be replaced or replenished. Meanwhile, this time the device is not useful. This poses serious problems in placing sensors in remote location devices, such as sensor-net nodes and bio-implantable devices. Novel devices are needed to convert available energy to electrical power. Some solutions include photovoltaic and piezoelectric transducers [1]. The LEPG is the latest energy scavenging device.

Seiko has demonstrated the ability to harvest energy from rotational torque with an electromagnetic power generator in their Kinetic Series watches. We have previously demonstrated this same ability with an electrostatic solution, which takes advantage of MEMS process efficiencies and produces output voltage swings greater than 40 volts. Our previous generator converts rotational energy to electrical energy with a fixed-charge variable-area capacitor. Exploiting the relationship

$$V(t)=Q/C(t), C(t)=\epsilon A(t)/d \quad [1]$$

we are able to convert a variable area into a variable voltage for power harvesting.

To take advantage of linear oscillations, we could easily change the geometry of the previous device and fabricate a moving-mass suspended by springs. This is still a fixed-charge, variable-area capacitor. A fixed-charge, variable-distance capacitor is essentially a microphone, which has been previously reported [2-4].

The work presented here explores a variable-permittivity capacitor.

$$C(t)=\epsilon(t)A/d \quad [2]$$

The effects of a variable permittivity are explored in freshman E&M books [5], but those examples use a solid dielectric. This would quickly destroy the Teflon surface unless a mechanism is employed to maintain a gap while allowing relative motion. This causes more friction and thus consumes valuable energy. Instead of using solids and more processing steps to create micro springs or sliders, our solution exploits the near-zero friction of a high contact angle liquid on the dielectric.

Experiments with liquid water stalled when the liquid experienced electrowetting [6]. Using silicone oil to prevent electrowetting would enable the use of water, but it is not clear what effect this would have on the required fixed charge. Mercury is a liquid at room temperature, and does not appear to suffer from electrowetting. It has a contact angle of $\sim 150^\circ$ on Teflon. Mercury, a conductive metal, is equivalent to a dielectric of infinite permittivity.

With low friction and heavy mass, the mercury will remain fixed as we subject the capacitor to linear oscillatory motion.

THEORY

The LEPG can be described as a displacement current device, in which a constant charge embedded into the Teflon produces an image charge shared between the top and bottom electrodes.

$$Q = q_1(t) + q_2(t) = \sigma LW \quad [3]$$

Where Q is total charge implanted, q_1 and q_2 represent the free charge available at the electrodes, σ is the measured charge density, and L and W are the length and width of the active channel as can be seen in figure 1. By fixing the position of the implanted charge and assuming the charge to be of uniform depth, it acts as a uniform intermediate electrode. The first approximation assumes the charge resides entirely on the surface of the Teflon layer. This intermediate electrode allows us to describe the system as four separate capacitors.

Starting with a single capacitor, C_0 , we develop an expression for a variable-dielectric capacitor c_0' with a dielectric that enters the gap according to the area ratio $\alpha(t)$.

$$C_0 = \frac{\epsilon_0 A_0}{G} \quad [4]$$

$$c_0' = \frac{\epsilon_0 A_0}{G} (1 - \alpha(t)) + \frac{k_{\text{liquid}} \epsilon_0 A_0}{G} \alpha(t) = C_0 (1 + \chi_{\text{liquid}} \alpha(t)) \quad [5]$$

Where χ_{liquid} is $k_{\text{liquid}} - 1$

Now, we add in a second capacitor in series to C_0 to account for the charge implantation at depth Δ .

$$C_I = (C_0^{-1} + C_{\text{Teflon}}^{-1})^{-1} = \frac{\epsilon_0 k_{\text{Teflon}} A_0}{\Delta + k_{\text{Teflon}} G} \quad [6]$$

Incorporating a moving dielectric as shown in figure 1b and we get.

$$\begin{aligned} c_1 &= \frac{k_{liquid}\epsilon_0 A_0 \alpha(t)}{G}, c_2 = \frac{\epsilon_0 A_0 (1-\alpha(t))}{G}, \\ c_3 &= \frac{k_{Teflon}\epsilon_0 A_0 \alpha(t)}{\Delta}, c_4 = \frac{k_{Teflon}\epsilon_0 A_0 (1-\alpha(t))}{\Delta} \end{aligned} \quad [7]$$

Figure 1. a. Conceptual design b. Equivalent circuit.

The four capacitors exist between the top electrode and the implanted charge layer and reduce to a single equivalent capacitor as follows

$$\begin{aligned} \left(\frac{1}{c_1} + \frac{1}{c_3}\right)^{-1} &= \frac{k_{liquid}k_{Teflon}\epsilon_0 A_0 \alpha(t)}{k_{liquid}\Delta + k_{Teflon}G}, \\ \left(\frac{1}{c_2} + \frac{1}{c_4}\right)^{-1} &= \frac{k_{Teflon}\epsilon_0 A_0 (1-\alpha(t))}{\Delta + k_{Teflon}G} \end{aligned} \quad [8]$$

Then the equivalent capacitor is expressed as

$$c_1' = \left(\frac{1}{c_1} + \frac{1}{c_3}\right)^{-1} + \left(\frac{1}{c_2} + \frac{1}{c_4}\right)^{-1} = C_1(1 + \beta\chi_{liquid}\alpha(t)) \quad [9]$$

Which is similar to equation [5] - a single, variable-dielectric capacitor. The extra term is

$$\beta = \frac{k_{Teflon}/\Delta}{k_{liquid}/G + k_{Teflon}/\Delta} \quad [10]$$

For oscillatory motion with the droplet occupying the entire channel at \$t=0\$, the area of the channel that is affected by the liquid is described by

$$\alpha(t) = \left(\frac{1 + \cos(\omega t)}{2}\right) \quad [11]$$

For simplicity we ignore the spherical nature of the droplet.

Using the familiar \$V=Q/C\$, we can write the loop voltage as

$$v_{out} = \frac{q_1}{c_1'} - \frac{q_2}{C_2} = q_1 \left(\frac{1}{c_1'} + \frac{1}{C_2}\right) - \frac{Q}{C_2} \quad [12]$$

Where \$q_1\$ is the charge on the top electrode, \$q_2\$ is the charge on the bottom electrode, and \$C_2\$ is the capacitance between the implanted charge layer and the bottom electrode. \$q_2\$ was eliminated in favor of the constant charge \$Q\$ and \$q_1\$ by substituting [3] into [12].

Noting the obvious,

$$v_{out} = iR_L = -R_L \frac{\partial q_1}{\partial t} \quad [13]$$

and substituting [12] into [13], \$v_{out}\$ is eliminated:

$$-R_L \frac{\partial q_1}{\partial t} = q_1 \left(\frac{1}{c_1'} + \frac{1}{C_2}\right) - \frac{Q}{C_2} \quad [14]$$

In standard form, this is a linear, first order ODE.

$$\frac{\partial q_1}{\partial t} + \frac{1}{R_{load}} \left(\frac{1}{c_1'} + \frac{1}{C_2}\right) q_1 = \frac{Q}{R_{load}C_2} \quad [14]$$

Using:

$$m = \frac{1}{R_{load}} \left(\frac{1}{C_1(1 + \beta\chi_{liquid}\alpha(t))} + \frac{1}{C_2}\right) \quad [16]$$

$$\begin{aligned} n &= \frac{Q}{R_{load}C_2} \\ \mu(t) &= e^{\int m dt} = e^{\frac{t}{R_{load}C_2}} e^{\frac{1}{R_{load}C_1} \left(\frac{1}{1 + \beta\chi_{liquid}\alpha(t)}\right) dt} \end{aligned} \quad [17]$$

the solution is given by:

$$q_1 = \frac{\int \mu(t) n dt}{\mu(t)} + \frac{Const}{\mu(t)} \quad [18]$$

Numerical methods must be employed to solve this equation. The current, output voltage, and power can then be described as:

$$i = -\frac{\partial q_1}{\partial t}, v_{out} = iR_{load}, P_{out} = iR_{load}^2 \quad [19]$$

FABRICATION

Fabrication of the LEPG is shown in figure 2. Glass plates with patterned metal are the starting capacitor electrodes. An 8μm thick Teflon AF is spun onto the bottom plate, and 0.5μm Teflon onto the top plate [4]. The Teflon AF layer on the bottom plate is then implanted with electrons from a back-lighted thyratron to form the electret [7]. The spacer (which also provides the liquid chamber) is made by casting Sylgard 184 PDMS onto a CNC-machined mold (figure 3) and bonded to the bottom plate with epoxy. For this demonstration, a liquid mercury droplet is used to partially fill the chamber on the bottom electrode. The top electrode plate is then bonded to the spacer to finish the device (figure 4). Cavity dimensions for Device 3 are \$W=2.3mm\$, \$L=4.812mm\$, and \$H=2.3mm\$ for a droplet of 50μL. Cavity

dimensions for Device g are W=3.5mm, L=9.4mm, H=4.45mm for a droplet about 600 μ L.

Figure 2. Process Flow a. deposit metal on glass substrate b. pattern metal c. spin-on Teflon AF d. mask design used in step b.

Figure 3. Mold Master for Sylgard 184 and peeled PDMS.

Figure 4. Assembled LPG Devices 3.

EXPERIMENTAL DETAILS

Power generation experiments are performed using a shielded box mounted to Labworks Inc. ET-132-2 electrodynamic shaker (figure 5.), which is driven sinusoidally by a HP33120A function generator through a power amplifier. The acceleration of the power generator is measured using an Endevco256HX-10 accelerometer. Both the acceleration and generator voltage waveforms are averaged over 256 data sets. The shaking frequency is varied from 10Hz to 60Hz, while the rms acceleration is kept constant through

the experiments. The LEPG is connected to a resistive load and the voltage across the load is measured from a National Semiconductor LF356N op-amp used as a 10^{12} Ohm input impedance voltage buffer.

Figure 5. Test Setup for LEPG

DATA ANALYSIS

Power generated versus frequency from two LEPG devices of different size suggests that device geometry can be optimized for shaking parameters (figure 6). In this graph we see the maximum power of 0.25 μ W was produced with Device 3, the same shown in figure 4. The waveform of Device 3 appears to be frequency shifted by 19Hz with respect to Device g, with secondary peaks being larger in magnitude. The frequency shift is expected since channel length for Device g is $\sim$ 50% longer than Device 3. The measured masses are: Device 3 is 2.7g and Device g is 5g, including mercury.

Figure 6. Power versus frequency for 2 devices of different channel length and height.

Figure 7 also shows that for a single device, power generation versus frequency is load dependent. The figure shows that power is scaled, but not translated in frequency for different loads. Thus far, insufficient testing precludes determining the optimum load.

Figure 7. Power versus frequency for a single device with 2 different loads.

Figure 8 shows open circuit voltage increasing with acceleration up to 16Hz for a single device. From 16Hz to 24Hz the voltage output exceeds the buffer amplifier range of 30Vpp. For frequencies greater than 24Hz the mercury droplet begins to oscillate in multiple modes at frequencies other than the driving frequency. This lowers rms voltage output. The shaker setup does exhibit slight resonant modes in the y and z axes, however, this phenomenon is observed on all test samples, and appears to be related to cavity and/or liquid dimensions as shown in figure 6.

Figure 8. Open circuit voltage and acceleration versus frequency for constant displacement.

The voltage response of figure 9 is clipped, but it is apparent that system response is related to the driving function. The driving function being fed to the shaker is sinusoidal, but this frequency is below the specifications listed on the accelerometer. Watching the shaker, the motion is visibly not sinusoidal. As acceleration passes through its maximum, the voltage output passes through zero. Equivalently, current is proportional to velocity.

Lifetime tests were performed on Device g. The test consisted of a repeating, linear frequency sweep between 1 and 60Hz over 30second intervals for 2 weeks. There was no noticeable change in the output power or waveform over this time.

Figure 9. Open circuit voltage and acceleration waveforms, at given amplitude and frequency.

CONCLUSIONS

We have produced a variable-permittivity power generator with maximum power output of $0.25\mu\text{W}$ and over 30Vpp open circuit voltage. The trend shows an increase in power generated for smaller devices and higher frequencies. For load resistances tested, there is no evidence that maximum power output shifts in frequency with load resistance. Further work should probe the effects of scaling device dimensions and varying liquid volume fractions. Liquid dielectrics with dielectric constant less than infinity should also be explored.

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