ELECTROSTATIC ENERGY HARVESTER FOR LOW-FREQUENCY VIBRATION BY HUMAN PHYSICAL MOTIONS USING LIQUID

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Abstract: The frequency generated by human physical motions is below 10 Hz. However, most previous energy harvesters are designed for the frequency over 100 Hz, so it is difficult for them to be applied to human physical motions. In this paper, we proposed and demonstrated a new electrostatic energy harvester for low level vibrations by using liquid. The proposed energy harvester had the large capacitance variation over 70 pF at extremely low frequency of 1.5 Hz. The generated power at 1.5 Hz was 0.3 µW theoretically when it was in voltage constrained conversion and an auxiliary voltage was 50 V.

Keywords: low frequency, human physical motions, liquid, electrostatic energy harvester, vibration

INTRODUCTION

A permanent power source harvesting ambient energies is an essential component to realize self-sustainable sensor nodes for ubiquitous networks. It can greatly reduce costs for maintenance of sensor nodes and consumption of batteries. So, a number of permanent power sources like a photovoltaic cell, a thermoelectric device, and a micro-generator have been actively researched for a decade.

Among them, an energy harvester using ambient vibrations is one of the leading candidates because it can easily scavenge energies from movable objects such as a machine and human [1-3]. However, the operation frequency of most previous energy harvesters using vibration is over 100 Hz due to their stiff spring and low mass. So, it is difficult for them to be applied to human physical movements because frequencies generated by human motions are below 10 Hz [4]. Moreover, some of them were designed to be excited by pre-determined directional motions, so power generated by human random motions is relatively low [5].

In this paper, we proposed a new electrostatic energy harvester using liquid for a vibration with low frequency below 10 Hz and random directional motions generated by human physical movements and demonstrated its possibility.

PROPOSED ENERGY HARVESTER

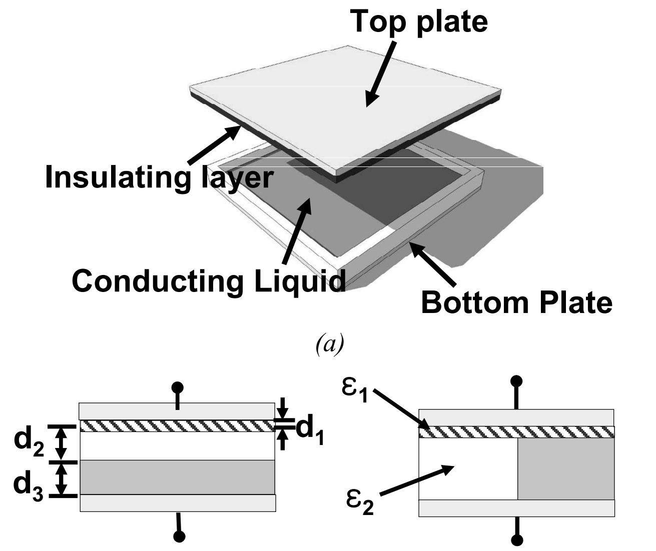
Liquid with low viscosity has extremely sensitive reactions to the external motions. At least once, all of us might have had experiences that water in a glass was easily overflowed when we were walking or running with it in our hand. Based on this feature, we propose a new electrostatic energy harvester using liquid.

Figure 1 explains the structure of proposed device and its operation principle. It consists of a top metal plate with an insulating layer, a bottom metal plate without an insulating layer, side walls and conducting liquid. Because conducting liquid was electrically connected to the bottom plate, it serves as a movable metal plate. Initially, the capacitance of the device is small due to large air gap of d_2 as illustrated figure 1(b). As the device shakes according to external motions, the liquid slops from side to side and touches the insulating layer as illustrated figure 1(c). Equation (1) and (2) indicate theoretical capacitance values of initial stage and excited stage respectively.

$$C_{initial} \approx \frac{\varepsilon_1 \varepsilon_1}{\varepsilon_1 d_2 + \varepsilon_2 d_1} S \qquad (1)$$

$$C_{excited} \approx \frac{\varepsilon_2 d_2}{(d_2 + d_3)^2} S + \frac{\varepsilon_1 d_3}{d_1 (d_2 + d_3)} S \qquad (2)$$

where d_3 is thickness of conducting liquid, S is overlap area of top plate and bottom plate, and ε_1 and ε_2 indicate permeability of insulating layer and air gap respectively.



(b) (c)

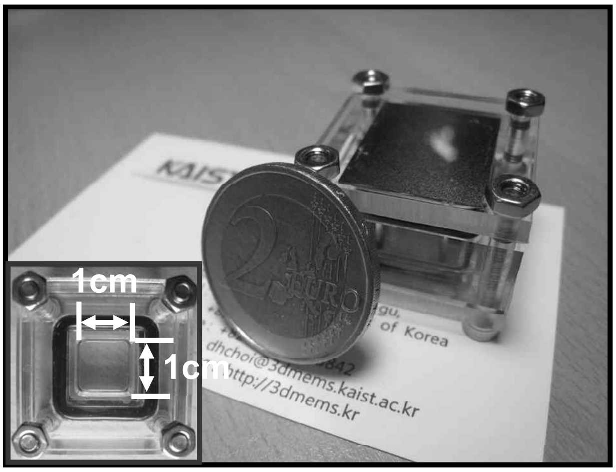
Figure 1. (a) Schematic view of proposed electrostatic energy harvester (b) initial stage with minimum capacitance (c) excited stage with maximum capacitance

In electrostatic energy harvester, variation of capacitance is a key factor since generated power is proportional to it [6]. Equation 3 shows the ratio of capacitance between initial and excited stage. If the device is designed as insulating layer of d_1 is much thinner than air gap of d_2, it has large variation of capacitance. So, we expect that this device has a great possibility to harvester energies efficiently from human physical movements

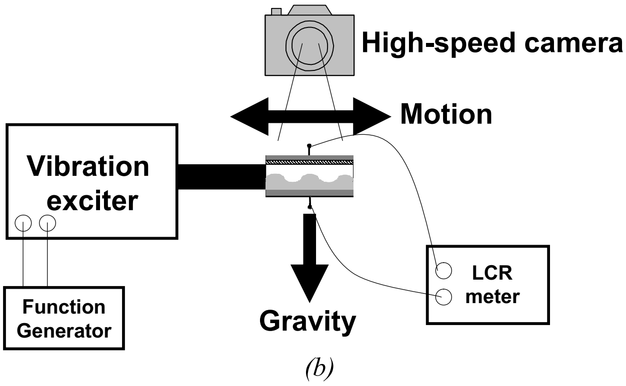
$$C_{ratio} = \frac{\varepsilon_1 d_2}{2\varepsilon_2 d_1} \approx \frac{d_2}{2d_1} \quad \text{assuming } d_2 = d_3 >> d_1 \quad (3)$$

PROTOTYPE AND MEASUREMENT

In order to verify the validity of proposed energy harvester, we made a prototype of electrostatic energy harvester. Figure 2(a) shows a photograph of our prototype. 100 nm-thick gold thin films evaporated on silicon substrate were used as top and bottom plates, and a 30 μm-thick adhesive polymer was used as an insulating layer. It had a cavity of $1\times1\times1cm^3$ for conducting liquid, and a solution saturated with K^+ and Cl^- ions was used as conducting liquid.



(a)



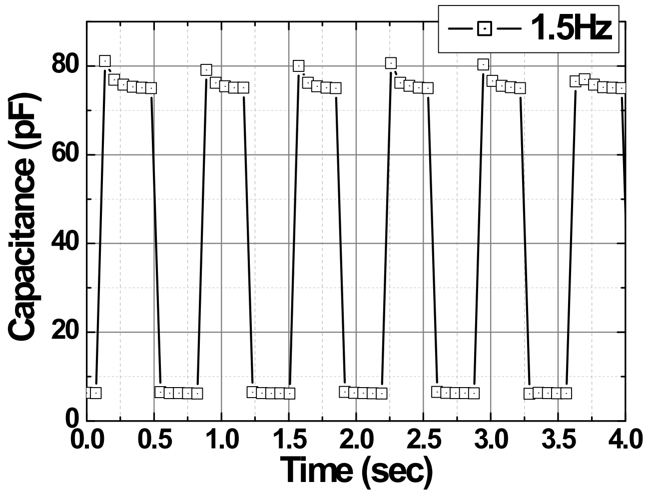
(b)

Figure 2. (a)Photographs of the fabricated device (It has a cavity of 1 cm^3- volume as shown in inset) (b) A schematic diagram of the experiment setup to measure capacitance variation.

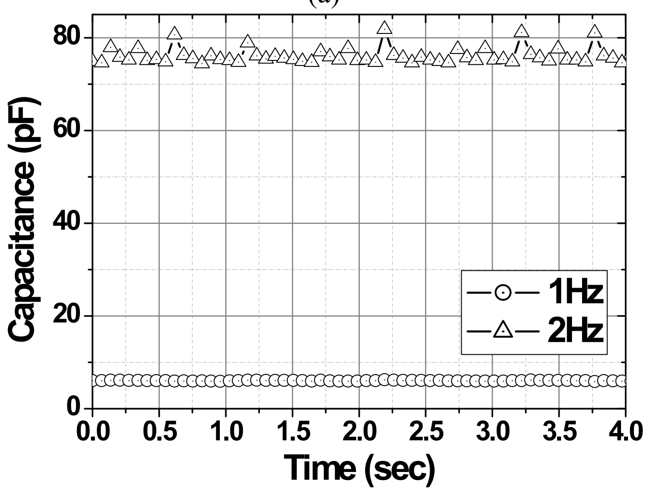
Figure 2(b) is a schematic diagram of the experiment setup to measure capacitance variation of our device. The proposed energy harvester was mounted on a vibration exciter, and variations of capacitance were measured by precision LCR meter. Input vibrations applied by the vibration exciter had horizontal and sinusoidal motions with a constant peak-to-peak value of 2.5 cm, and their frequencies were varied between 1 Hz and 10 Hz. It is very difficult to predict theoretically the precise motion of liquid in cavity, so we used a high speed camera to analyze the motion of liquid.

EXPERIMETAL RESUTLS

Figure 3 shows measured results of the device with conducting liquid of 800 μL. At 1.5 Hz, the capacitance was varied well. Its minimum and maximum value was about 6 pF and 80 pF, respectively. This result at 1.5 Hz was just as we had expected, and showed the great promise as an energy harvester for low level vibration.



(a)



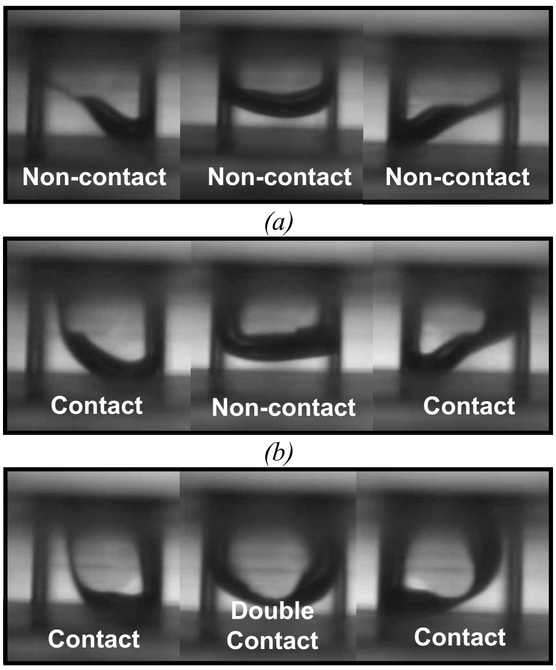
(b)

Figure 3. Capacitance variation in accordance with horizontal and sinusoidal motions having a peak-to-peak value of 2.5 cm (a) 1.5 Hz external motion (b) 1 Hz and 2 Hz external motion

However, the capacitance in motions of 1 Hz and 2 Hz remained unchanged at the minimum and maximum values as shown in figure 3(b). In actuality, we expected that the proposed device had a good performance in wide frequency range, because there were no mechanical spring in it and liquid was very sensitive in wide frequency range. Figure 4 explains the reason why the device has a narrow operation frequency. In accordance with the photographs, liquid motions can be classified with three motions.

- If an applied acceleration is below proper level, the liquid cannot touch the top side, so its capacitance is in the low level. (figure 4(a))
- Applying proper acceleration, the behavior of liquid is clearly compartmentalized into contact and non-contact stage (figure 4(b)). Therefore, its capacitance is varied periodically.
- When it is in over proper acceleration, liquid is always connected with top side. So its capacitance isn't changed near a high level (figure 4(c)).

Therefore, when only applying proper acceleration like figure 4(b), the capacitance was periodically varied according to the clear compartmentalized contact and non-contact behavior. It seems that these behaviors are caused by surface tension on the surface of the insulating layer and side walls of the cavity. Figure 5 shows the impulse response of our device. It takes several second for liquid to go back to initial stage after the abrupt movement. Therefore, if the external movement was faster than settling time of liquid, the capacitance remained in high level.



(c)

Figure 4. Photographs of moving liquid in cavity observed by a high-speed camera. (The volume of liquid was 500 μL.) (a) below proper acceleration (b) at proper acceleration (c) over proper acceleration

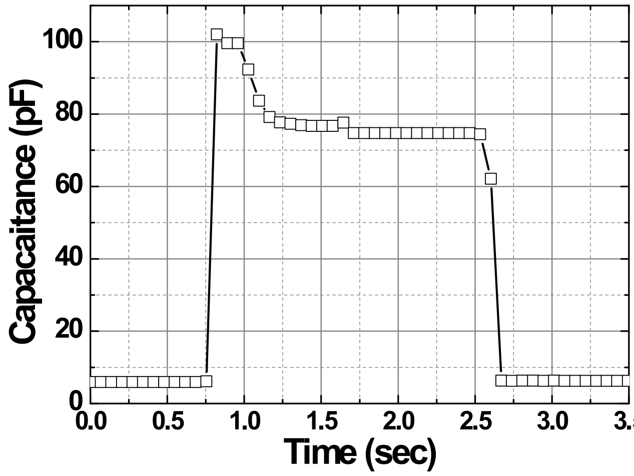


Figure 5. The response of the device to the abrupt movement like impulse with 1cm-displacement (The amount of liquid was 800 μL.)

As another feature of this device, operation frequency and capacitance variation of our device can be easily controlled by the amount of conducting liquid. Like other conventional energy harvesters, mass is one of important factors influencing its operating frequency. Therefore, the operation frequency is lower as the amount of conducting liquid is increased. The air gap of d_2 also has a decisive effect on its operation frequency and capacitance variation. As increasing the amount of liquid, the gap is decreased. So, conducting liquid can easily touch the top plate, and the overlap area (S) becomes larger. Figure 6 shows results controlling the amount of liquid. An energy harvester with 2.5 mL of conducting liquid had the operation frequency of 2.5 Hz and capacitance of 170 pF. On the other hand, in case of a device containing 4 mL of conducting liquid, its operation frequency and the variation value of capacitance were 3 Hz and 240 pF respectively.

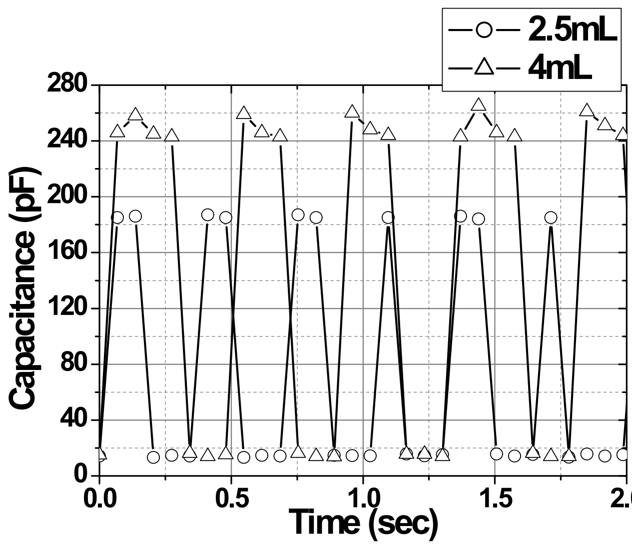


Figure 6. Capacitance variation according to the amount of liquid and d_3 (The volume of the cavity for conducting liquid was 9 cm^3.)

CONCLUSION AND DISCUSSION

The proposed energy harvester has advantages to react easily to motion with low frequency, so it can used as a power source for wearable computer or body sensor networks. The energy harvester proposed in this paper had the large capacitance variation over 70 pF at extremely low frequency of 1.5 Hz. The generated power at 1.5 Hz was theoretically 0.3 μW when it was in voltage constrained conversion and an auxiliary voltage was 50 V. Our device has also some problems to work out. The first is its narrow working frequency, and the second is that its miniaturization is very hard due to the effect of mass and surface tension. However, these problems can be solved by optimizing its structure. Therefore, further researches will be done to reduce the effect of surface tension by changing the pattern of top plate, the amount of liquid and so on. Especially, we expect that well-designed top plate relieves the surface tension.

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