Micro-Machined Variable Capacitors for Power Generation

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ABSTRACT

Variable capacitors are key elements in electrostatic micro-power generators. In such devices inertial forces are used to do work against the electric field of the capacitor, thereby converting mechanical energy to electrical potential energy that can be extracted by a suitable circuit. Applications are envisaged in portable, wearable or implantable electronic devices where body motion could provide the mechanical energy source. This paper describes the fabrication and initial testing of a micro-engineered variable capacitor for power generation. The measured capacitance of the device varies from 100 pF to around 1 pF as the mass moves from initial to final position, corresponding to a hundred-fold increase in voltage if the device is operated in constant charge mode. Initial tests of the capacitor on a vibration system (10 Hz) have shown that a periodic high voltage output of 2.3 kV can be generated if the capacitor is charged by a voltage source of 26 V. This corresponds to an energy conversion rate of 2.4 \mu J per cycle, or 24 \mu W at a vibration frequency of 10 Hz.

INTRODUCTION

Most micro-electro-mechanical systems (MEMS) today utilise macroscopic power sources. This places some limits on the applications of MEMS devices. For example, in some potential applications, these micro-machined devices have to be completed embedded or fabricated in the structures where external power is not accessible. Miniaturized implantable medical sensors are one of these applications. Although high-energy batteries are currently used to power these devices, this solution is less than satisfactory. Batteries are normally bulky and contain a finite amount of energy, their shelf life is limited and the chemicals contained in the batteries may be toxic. In search for an alternative power supply for these applications, micro-machined power suppliers have shown a promising advantage for their miniaturization, which can be easily integrated into these MEMS devices. Some of them can be specially designed to convert the energy in the environment into electrical power. Thus these MEMS devices will become self-powered.

Although miniaturized self-contained power supplies are not a new idea, it has not attracted much attention until recently. Attempts have been made to design and fabricate micro-machined power generators utilising thermal energy [1-4], kinetic energy of gas flow [5] and mechanical energy converted by a piezoelectric element [6] or a permanent magnet [7-9].

Recently, we designed and fabricated a micro-machined mechanical-electrostatic power generator. The main reason why such an approach was chosen is that our particular interest lies in the possible applications in wearable, carried and medical implant electronics. In these applications, light energy is normally not obtainable. Although living bodies contain thermal energy, it is not realistic to convert this energy into electrical energy. This is because the generator of this kind works on the temperature gradient. The temperature differences within living bodies are small. Kinetic energy from the volume flow of fluids requires a comparatively high reservoir fluid pressure, and more crucially, require the device to present
an obstruction to the fluid flow, with obvious safety implications. As for as the transduction mechanism, piezoelectric and electromagnetic transducers are more complicated for fabrication. It is more difficult to miniaturize them to a dimension which is compatible to body implantation. The electrostatic transducer is simple in structure. Basically, it is a variable capacitor which can be formed between any two metallic plates separated by a dielectric material. Tashiro et al [10] reported an electrostatic power generator that harnesses the motion of a living body. A honey-comb-type variable capacitor with a capacitance variation of 32 – 200 nF was used to convert mechanical energy into electrical energy. An output of 58 µW was reported to be generated from this generator with a constant charging voltage of 24 V and a load of 1.0 MΩ. However this power generator is not a micro-machined device.

The key element of an electrostatic micro-machined power generator is a variable capacitor, which can convert mechanical energy into electrical energy by means of the work done by an external force against the electric field formed between the two plates of the capacitor. This paper will present the structure and the results of the initial test of a micro-machined variable capacitor. Although the external circuit for power extraction from the capacitor is still under design, the operational principle of the power generator will be also addressed.

DEVICE STRUCTURE AND OPERATIONAL PRINCIPLE

The cross-section of the variable capacitor is schematically shown in Figure 1. A gold proof mass, supported on a highly flexible polyimide membrane, is suspended between a silicon top plate and a quartz base-plate. Patterned metal films on the base-plate and the membrane form the fixed and moving plates of the capacitor, the latter being connected to the external circuit only at the extremes of its travel where it makes contact with plated contact studs.

Power generation is achieved in this device by pulling apart the base plate and the movable plate and then extracting energy stored in the electric field. During the input phase, the mass is forced against the contact studs on the base plate, connecting it to a charging circuit, which brings it to a starting potential. In response to motion of the frame, which is attached to the host, the mass is accelerated sufficiently in the opposite direction and moved to the top plate where it will be stopped by the contact studs on the top plate. The energy stored in the capacitor is then extracted by an output circuit. The power extraction circuit of the generator is shown in Figure 2. The initial charge delivered to the capacitor occurs through a half-cycle quasi-resonant action with L1 when the electronic switch Q1 is turned on. Charge is recovered from the capacitor, at a higher voltage, by another quasi-resonant action with L2 which stores energy in L2 during one phase and then releases it the charging source B1 during a second phase. The operation is self-synchronous. The pre-charge operation is initiated when
the moving plate makes contact with the $V_{in}$ terminal. The charge delivered is governed by the Q1 on-time set by the control circuit. The discharge is initiated by the contact with the $V_{out}$ terminal and is automatic.

![Figure 2 Schematic of the proposed control and power circuit.](image)

**RESULTS AND DISCUSSIONS**

The capacitance measurement of the device was conducted using a PM 6303 RCL meter. The device was mounted on a fixed stage. The movable plate of the device was attached to a micrometer which can move the plate up and down with a resolution of 10 μm. Capacitance was measured between the movable plate and the base plate. The measured capacitance is plotted against the gap between the two plates. The result is shown in Figure 3.

![Figure 3 Variation of capacitance throughout the travel distance of the movable plate.](image)

It can be seen that the measured capacitance (squares) of the device varies from $C_1 = 100$ pF to around $C_2 = 1$ pF as the mass moves from bottom to top, corresponding to a hundred-fold increase in voltage if the device is operated in constant charge mode. The measured capacitance decreases more slowly than that calculated from an air gap capacitor (dotted line). This is probably due to non-parallelism of the movable plate and the base plate.

A leakage measurement was also carried out. The capacitor was charged to an initial voltage $V_0$ at its minimum gap position (input phase) and then disconnected from the charging source. The movable plate was isolated from both charging source and top contact for delay time $t_D$, while held at an intermediate capacitance $C_m$, and then moved up to its maximum gap position (output phase), and the voltage recorded. The discharge transient amplitude is normalized to
the original charging voltage and plotted against the delay time as shown in Figure 4. If we assume the device has a leakage path resistance $R$, then the discharge transient amplitude can be described by following formula:

$$V_f = \frac{C_1}{C_2} V_0 e^{-\frac{t_0}{RC}}$$

Figure 4 Reduction in the discharge transient amplitude against time.

Figure 4 indicates that the time constant for decay of the charge is well over 100 s. This suggests that there will be negligible charge leakage when the device is in operation.

Initial discharge tests of the capacitor were conducted on a vibration system. The experimental set-up is schematically shown in Figure 5. The variable capacitor was charged by a voltage source of 26V when the movable plate contacts the contact studs on the base plate during vibration. When the movable plate travels to the upper contact studs, the discharge occurs via an operational amplifier with a gain set to $-1/1000$.

Figure 5 Experimental set-up for measuring periodic discharge, with the device mounted on a vibration testing system.
In Figure 6, it can be seen that periodic discharges can be generated from the device. The time intervals of the periodic discharges correspond to the vibrating frequencies of the vibration system (marked correspondently). Variations in the apparent amplitude of the discharges is simply due to limitation in the data acquisition rate of the oscilloscope in the displayed time span. The discharge test was carried out in the frequency range from 5Hz to 100Hz. The device was shown to be operational in this frequency domain.

If the time scale is expanded, a complete discharge transient can be viewed. Figure 7 shows the discharge transient when the device is vibrating at the frequency of 10Hz. The amplifier output is 2.3V, i.e. the actual output of the device is 2.3kV. Since the output of the charging source was set to 26V, this corresponds to an 88.5 fold increase in voltage, which is in reasonable agreement with the ratio of capacitance increase of 100. The difference may results from parasitic capacitances in the system. The energy stored in a capacitor is simply \( \frac{1}{2}CV^2 \), and the maximum energy generated from the device will be the difference between energies stored in the capacitors at minimum and maximum gap positions. In the present case this corresponds to an energy conversion rate of 2.4 \( \mu \)J per cycle, or 24 \( \mu \)W at a vibration frequency of 10Hz.
CONCLUSIONS AND FUTURE WORK

A prototype variable capacitor has been designed and fabricated. The capacitance measurement shows that the capacitance of the device varies from 100pF to around 1pF, corresponding to a 100-fold increase in voltage. The leakage test shows that the time constant is well over 100s, which is much longer the working cycle of the device, indicating that charge leakage is negligible in operation. This is certainly necessary to the achievement of high efficiency in low frequency applications. Discharge tests on a vibration system proved that the device is operational in a wide frequency range and that a high output voltage can be generated from the device. Although the variable capacitor is the key element of the electrostatic type power generators, a complete generator has to have a power harvest circuit. The design of such a circuit has been described, and implementation is currently under way. The efficiency of the power generator not only depends on the variable capacitor, but also the circuit. Therefore a systematic test on a complete power generator is needed. The existing variable capacitor is a hybrid integrated device; a more integrated structure will be designed and fabricated to meet such applications as medical implants.

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