ASYMMETRIC CHARGE TRANSFER PHENOMENON AND ITS MECHANISM IN SELF-EXCITED ELECTROSTATIC ACTUATOR

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ABSTRACT

We observe the asymmetric charge transfer phenomenon and present its mechanism in self-excited electrostatic actuator for the first time. When a conductive cantilever is excited into oscillation between two electrodes under DC voltage, it is observed to transfer more charge when it contacts the negative electrode than the positive electrode. The mechanism of this asymmetric charge transfer phenomenon is investigated and it is indicated that the amount of the transferred charge, which is directly related to output power, increases with the applied DC voltage and the parasitic capacitance at the fixed end of the cantilever. As such, this work provides further understanding and guidance for output power optimization design of the self-excited electrostatic actuator.

INTRODUCTION

In recent years, the rapid development of micro robots in centimeter scale to millimeter scale, such as micro flying insects [1, 2] and micro crawling robots [3], has set off a new wave of research in micro actuators [4]. Among the existing micro actuators, self-excited electrostatic actuator demonstrates promising prospect due to its high energy conversion efficiency (90%) and light weight [4]. However, the actuator's output power still awaits to be enhanced for faster crawling robots or untethered flying robots. To optimize the electrostatic actuators for higher output power, the first step is to understand the fundamental mechanism of the oscillator in the actuator.

Since the commonly used electrostatic oscillators are designed for micro or nano electronic components, the mechanism study for performance optimization mainly focuses on lower power consumption or higher frequency response [5]. As for electrostatic actuators used in the field of micro robots in millimeter to centimeter scale, the fundamental mechanism of the electrostatic oscillators in actuator still remains unclear [2, 3]. As a consequence, the study on output power optimization is a comparatively less explored area since there is a serious lack of guiding theory.

The main purpose of this investigation is to look into the fundamental mechanism of charge transfer in electrostatic actuator for output power optimization. In this investigation, electrostatic actuators with different cantilevers and electrodes are tested and the amount of transferred charge are measured experimentally. The asymmetric charge transfer phenomenon is explained by analyzing the electron flow in the actuator during oscillation. An energy method is used to analyze the input power and output power of the actuator. The test results and theoretical analysis provide further understanding and guidance for output power optimization of the previously developed self-excited electrostatic actuator.

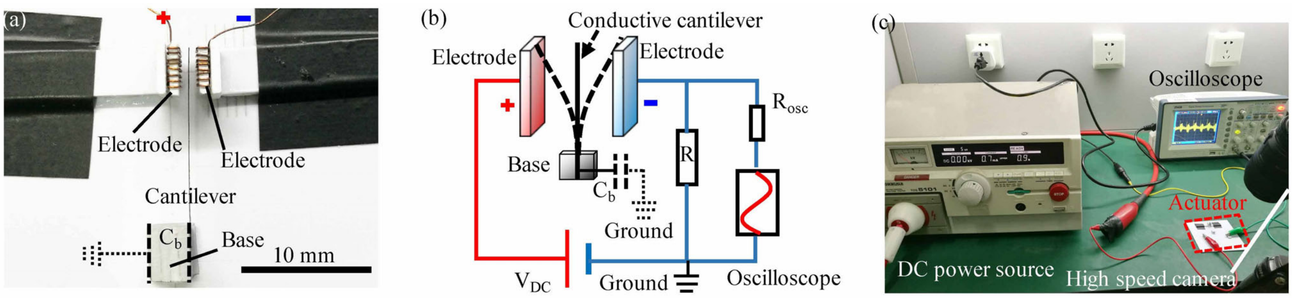

Figure 1: (a) Optical photo of an electrostatic actuator to demonstrate its configuration. (b) Schematic diagram of the electrostatic actuator. A digital oscilloscope is connected to the circuit to measure the voltage across the resistance R. (c) Optical photo of the test platform and a high speed camera is used to capture the oscillation process of the actuator.

EXPERIMENTAL SETUP

Figure 1a presents an optical photo of the electrostatic actuator with simple structure which includes two electrodes, a conductive cantilever and a base. The cantilever is fixed to the base and put in the middle of the gap between the two electrodes, which are connected to the positive and negative pole of a DC power source respectively. This setup is consistent with the electrostatic actuator presented in [6]. When a sufficient DC voltage is applied to the electrodes, the cantilever will be excited into sustainable oscillation.

To fabricate the electrostatic actuator, a carbon fiber plate with thickness of 60 μm is cut into the cantilever plate with length of 15 mm and width of 1.5 mm by using laser cutting technique. A cooper wire with diameter of 0.2 mm is utilized to wrap around a 5 mm × 5 mm PVC plate to form the cylinder electrodes. The thickness of the PVC plate is 1 mm. The base is also made of PVC plate. It is noted that the electrodes and the base are all glued to a large insulative substrate made of PVC plate. Since the cantilever is insulated from ground by the base and substrate, it can be considered that a parasitic capacitor, as shown in Figure 1a, is connected between the cantilever and the ground.

Figure 1b illustrates the schematic diagram of the electrostatic actuator. A resistor R is connected to the negative pole and an oscilloscope is used to measure the voltage across R during the oscillation. Then the current flowing through R can be calculated based on Ohm's law and the amount of transferred charge can be obtained by integrating the total current in the circuit.

$$Q = \int_{t}^{t+\Delta t} \left(\frac{U_R}{R} + \frac{U_R}{R_{osc}} \right) dt \tag{1}$$

Where U_R is the voltage across R and R_{osc} is the resistance of the oscilloscope.

Figure 1c shows an optical photo of the test platform and a high speed camera is utilized to capture the oscillation process of the cantilever. Considering the large bending stiffness of the cantilever plate, it requires extremely high DC voltage to induce oscillation, and that may cause breakdown of the actuator. To reduce the DC voltage that is required to excite the oscillation, a small static force is applied to the cantilever and then removed quickly to form a initial disturbance of the cantilever. In that way, the cantilever will be excited into oscillation under a relative low DC voltage.

ASYMMETRIC CHARGE TRANSFER

According to equation (1), the amount of transferred charge can be obtained by measuring the voltage across R. Figure 2a shows measured U_R versus time under an applied DC voltage of 2.5 kV. It's observed that the oscillation of the cantilever results in two types of pulse voltages with different amplitudes. To determine the relation between the frequency of the pulse voltages and the oscillation frequency of the cantilever, a high speed camera is used to capture the oscillation process at 3000 frames per second to obtain the oscillation frequency. The results reveal that the frequency of the pulse voltages equals to the oscillation frequency of the cantilever. Therefore, it is reasonable to conclude that the pulse voltage (or electron flow) occurs when the cantilever contacts the electrodes and the cantilever transfers different amount of charge when contacting different electrodes.

Figure 2b illustrates enlarged view of the voltage pulses with two different amplitudes. The ratio of primary peak to secondary peak is close to 2.5 : 1. It is observed that both voltage pulses increase to their maximum amplitudes vertically at the beginning and then decrease gradually with time. This can be explained by the collision process of the cantilever with the electrodes. When the cantilever contacts the electrode, the charges with different polarities recombine and large electron flow occurs instantly in the circuit and then decreases to zero after the cantilever detaching the electrode. Figure 2c illustrates normalized voltage pulses versus time. Both voltage pulses fit well with exponential decay model and the pulse widths are close to each other. The area covered by the curve of voltage pulse and the horizontal axis represents the amount of the transferred charge when the cantilever contacts the electrodes.

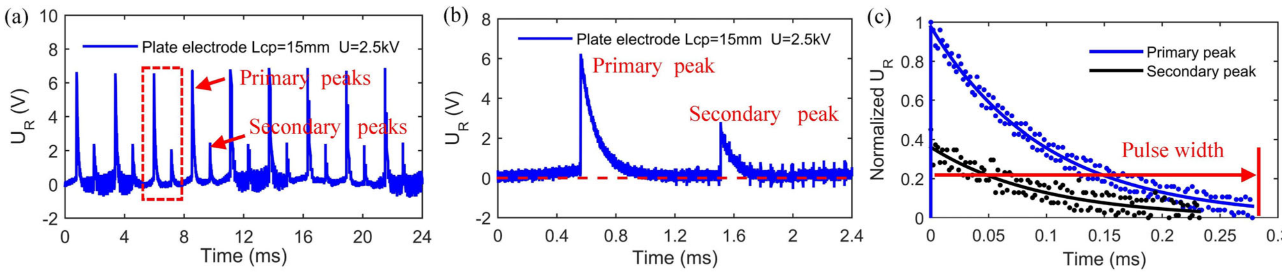

Figure 2: (a) Measured U_R versus time under an applied DC voltage of 2.5 kV. (b) Enlarged view of the voltage pulses versus time to demonstrate their variation trend over time. (c) Normalized voltage pulses versus time to calculate the amount of transferred charge.

CHARGE TRANSFER MECHANISM

To understand the fundamental cause of the asymmetric charge transfer phenomenon and its influence factors, the charge transfer mechanism is analyzed by looking into the electron flow in the circuit when the cantilever contacts different electrodes. Figure 3 illustrates the schematic diagram of the charge transfer process in a cycle.

(1) In electrostatic actuator, the cantilever and the positive electrode form a capacitor C_{a1}. Similarly, the cantilever and the negative electrode form a capacitor C_{a2}. The fixed end of the cantilever and ground form a parasitic capacitor C_b. The lower part of the cantilever outside the electrodes and ground form a parasitic capacitor C_c. Since the cantilever is electrically neutral before oscillation and the fixed end of the cantilever can only carry positive charge. When a DC voltage is applied, the free end of the cantilever carries negative charge Q_{ini} due to electrostatic induction. As a result, the free end of the cantilever will move toward the positive electrode to start the oscillation process, which is consistent with the experimental observations.

(2) When the cantilever contacts the positive electrode, C_{a2}, C_b and C_c are charged and the capacitance C_{a1} decreases to zero. Therefore, the cantilever carries a total amount of positive charge of Q_{a2}, Q_b and Q_c. From the view of electron flow, electron Q_b and Q_c flow to the ground and Q_{a2} flows through R to the negative electrode to charge the capacitor C_{a2}.

(3) The cantilever detaches the positive electrode and

moves toward the negative electrode with positive charge.

(4) The cantilever contacts the negative electrode and the positive charge is all neutralized. Since the electric potential of the cantilever decreases to zero, there is no potential difference between the cantilever and the ground. Therefore, only capacitor C_{a1} is charged and the cantilever only carries a amount of negative charge Q_{a1}. From the view of electron flow, the electron Q_b and Q_c flow through R to neutralize the positive charge on the cantilever and electron Q_{a1} flows through R to charge the capacitor C_{a1}.

(5) The cantilever detaches the negative electrode and moves toward the positive electrode with negative charge.

(6) The cantilever contacts the positive electrode and the capacitors C_{a2}, C_b and C_c are charged again. Electron Q_b and Q_c flow to the ground and Q_{a2} flows through R to the negative electrode.

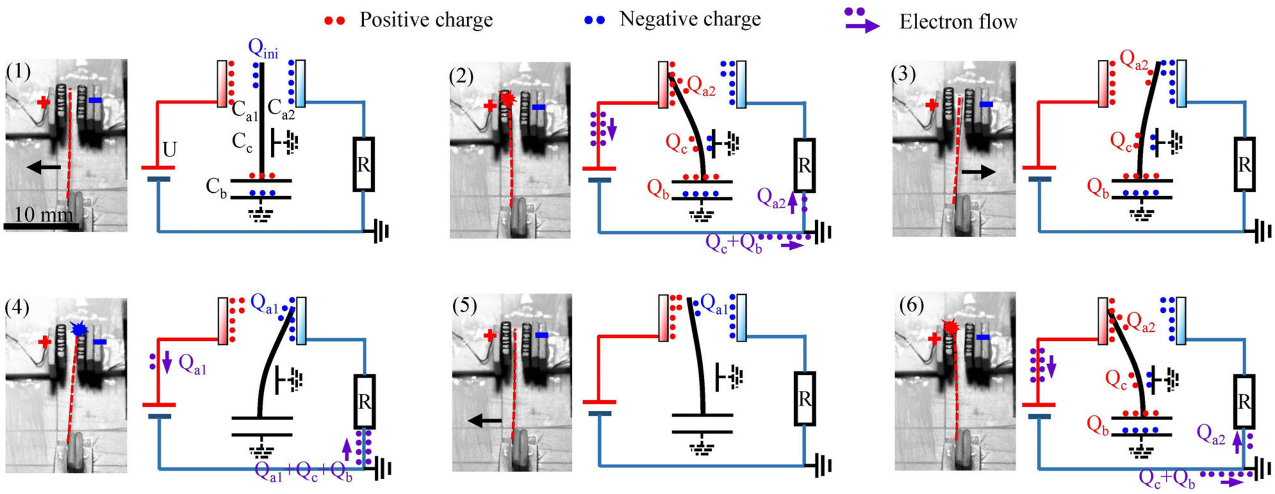

Figure 3: The schematic diagram of the charge transfer and electron flow process in a cycle.

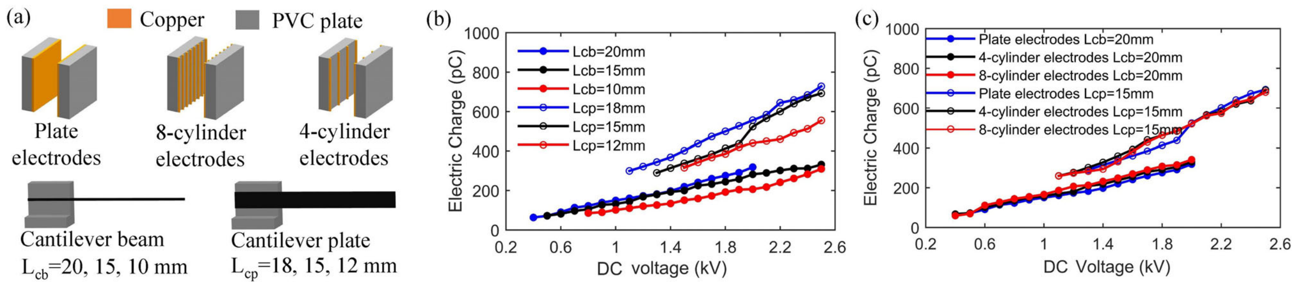

Figure 4: (a) Schematic diagram of different cantilevers and electrodes. The Ni-Ti cantilever beams have a diameter of 70 μm and three different lengths L_{cb}. The carbon fiber cantilever plates are 1.5 mm wide and 60 μm thick and also have three different lengths L_{cp}. The plate electrodes are made of 0.2 mm-thick copper plate. The cylinder electrodes are made of copper wire with diameter of 0.2 mm. (b) Transferred charge with respect to different cantilevers under different voltages. (c) Transferred charge with respect to different electrodes under different voltages.

Based on above analysis, the fundamental cause of the asymmetric charge transfer phenomenon is the existence of the parasitic capacitors C_b and C_c. The amount of transferred charge is determined by the sum of capacitance C_{a1}, C_{a2}, C_b and C_c. Considering the size of the cantilever is limited by the low weight budget and stringent size limitation of the micro robots, the most practical approach to increase the amount of transferred charge is to optimize the fixed condition of the cantilever for larger C_b.

To validate the charge transfer mechanism, electrostatic actuators with different cantilevers and electrodes are fabricated and tested. As shown in Figure 4a, the Ni-Ti cantilever beams have a diameter of 70 μm and three different lengths L_{cb} (L_{cb} = *10, 15, 20* mm). The carbon fiber cantilever plates are 1.5 mm wide and 60 μm thick and also have three different lengths L_{cp} (L_{cp} = *12, 15, 18* mm). The plate electrodes are made of 0.2 mm-thick copper plate. The cylinder electrodes are made of copper wire with diameter of 0.2 mm. During the test, the distance between the electrodes is set at 2 mm.

Figure 4b shows the amount of transferred charge with respect to different cantilevers under different voltages. The electrodes of the actuators in this case are all plate electrodes. It is observed that higher voltage leads to more transferred charge regardless of the cantilever types. This result is predictable based on the equation $Q = CU$. The result also reveals that cantilever plates can transfer more charge than cantilever beam. For both cantilever beam and cantilever plate, longer cantilever transfers more charge as shown in Figure 4b. These results agree well with the charge transfer mechanism. For different cantilevers, larger surface area of the cantilever at the fixed end leads to larger capacitance C_b and the larger surface area of the cantilever outside of the electrodes leads to larger capacitance C_c, which results in larger amount of transferred charge.

Figure 4c shows the amount of transferred charge with respect to different electrodes under different voltages. Cantilever beam with length of 20 mm and cantilever plate with length of 15 mm are selected for this test. The results show that the configurations of electrodes have no effect on the amount of transferred charge. According to the charge transfer mechanism, the amount of transferred change is affected by the capacitance of C_{a1} and C_{a2}, which are determined by the dielectric between the electrodes rather than electrodes themselves.

OUTPUT POWER ANALYSIS

To investigate the relation between the output power and the amount of transferred charge, the output power is derived by analyzing the energy of the oscillation system. The input energy of the actuator is the difference of system potential energy in different states. Figure 5 illustrates the equivalent circuit diagram of the electrostatic actuator. The capacitors C_{a2}, C_c and C_b are connected in parallel, and together they are connected in series with C_{a1}. The total potential energy of the system can be given as [5, 7]:

$$E = \frac{1}{2}kx^2 + \frac{1}{2}C_{a1}(U-U_f)^2 + \frac{1}{2}(C_{a2}+C_b+C_c)U_f{}^2 - (U-U_f)C_{a1}U \quad (2)$$

Where k is the stiffness of the cantilever and x is the displacement of free end of the cantilever and U_f is the electrical potential of the cantilever.

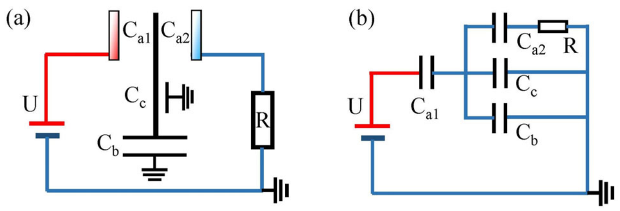

Figure 5: The equivalent circuit diagram of the electrostatic actuator.

When the cantilever contacts the positive electrode, U_f equals to the source voltage U and the capacitance C_{a1} decreases to zero. The potential energy of the system can be given as:

$$E_+ = \frac{1}{2}kx_+{}^2 + \frac{1}{2}(C_{a2}+C_b+C_c)U^2 \quad (3)$$

When the cantilever contacts the negative electrode, U_f and the capacitance C_{a2} decreases to zero. The potential energy of the system can be given as:

$$E_- = \frac{1}{2}kx_-{}^2 - \frac{1}{2}C_{a1}U^2 \quad (4)$$

Based on above analysis, the reduction of the potential energy or input energy in a cycle is:

$$\Delta E = 2(E_+ - E_-) = (C_{a1}+C_{a2}+C_b+C_c)U^2 \quad (5)$$

This result is consistent with the work done by the transferred charge in a cycle. In other words, the input energy increases with the amount of transferred charge.

$$\begin{aligned}\Delta E &= (C_{a1}+C_{a2}+C_b+C_c)U^2 \\ &= (Q_{a1}+Q_{a2}+Q_b+Q_c)U = Q_{total}U\end{aligned} \quad (6)$$

During the no-load operation of the actuator, the input energy is used to maintain the oscillation of the cantilever and it is dissipated by the damping forces. When a workload is applied to the cantilever, the output power can be given as:

$$P_{out} = P_{input} - P_{damp} = (\Delta E - \Delta E_{damp})f \quad (7)$$

Where f is the oscillation frequency. Since the dissipated energy per cycle is not easy to optimize, the most effective way to enhance output power is to increase input energy, which is mainly determined by the amount of transferred charge.

CONCLUSION

This paper describes an asymmetric charge transfer phenomenon and presents its mechanism in self-excited electrostatic actuator. The mechanism reveals that the underlying cause of the asymmetric charge transfer is the existence of the parasitic capacitors C_c and C_b. The energy analysis indicates more transferred charge leads to higher output power and the most effective approach to increase transferred charge is to increase the capacitance C_b. Future work aims at further enhancing the output power of the electrostatic actuator for future application in the field of micro robots.

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