SELF-LIFTING ARTIFICIAL INSECT WINGS VIA ELECTROSTATIC FLAPPING ACTUATORS

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ABSTRACT
We present self-lifting artificial insect wings by means of electrostatic actuation for the first time. Excited by a DC power source, biomimetic flapping motions have been generated to lift the artificial wings 5cm above ground (limited by the current experimental setup) under an operation frequency of 50-70Hz. Three achievements have been accomplished: (1) first successful demonstration of self-lifting electrostatic flying wings; (2) low power consumption as compared to other actuation schemes; and (3) self-adjustable rotating wing design to provide the lifting force. As such, this work can lead to a new class of electrostatic flapping actuators for artificial flying insects.

INTRODUCTION
Artificial flying insects can be considered as Micro Air Vehicles (MAVs) with wingspans of less than 3-5cm and potential applications in search, rescue, exploration, and reconnaissance [1]. These robots are designed to do maneuvers in limited spaces such as rooms, caves, and jungles that large flying robots won't be serviceable. To achieve such tasks, actuators of these robots are required to have biomimetic flapping motion (in terms of frequency, amplitude and trajectory etc.) with desirable simple design and low weight. The biomimetic flapping motion is the key to generate lift force, and the simple structural design is vital for autonomous flight. It has been a key challenge for current technologies to meet these requirements.

For the purpose of achieving fully autonomous flight, a few kinds of actuation schemes have been investigated to drive artificial flying insects, such as electrostatic actuator [2], piezoelectric actuator [3, 4], and DC motor [5, 6]. Among these schemes, the electrostatic actuator, which usually consists of fixed electrodes and moving electrodes (as flapping wings), is very attractive due to its low power consumption and ease of miniaturization. However, previous demonstrations have failed to generate effective lift force as the moving electrodes were not able to imitate the "rotational" flapping motions of real insect wings [2].

In 2013, an insect-scale flapping robot that achieves controlled and tethered flight has been demonstrated using piezoelectric flight muscles [3, 4]. Here, we demonstrate the first vertical lift motions of artificial insect wings via electrostatic flapping actuators [7]. The actuator can work at a resonance state under constant DC input without using any complex AC circuits, and directly drive the wings in a biomimetic way with measured lifting force up to more than 3mg. A prototype of the actuator has been designed and fabricated for the purpose of investigating its key characteristics in terms of wing motion and lift force.

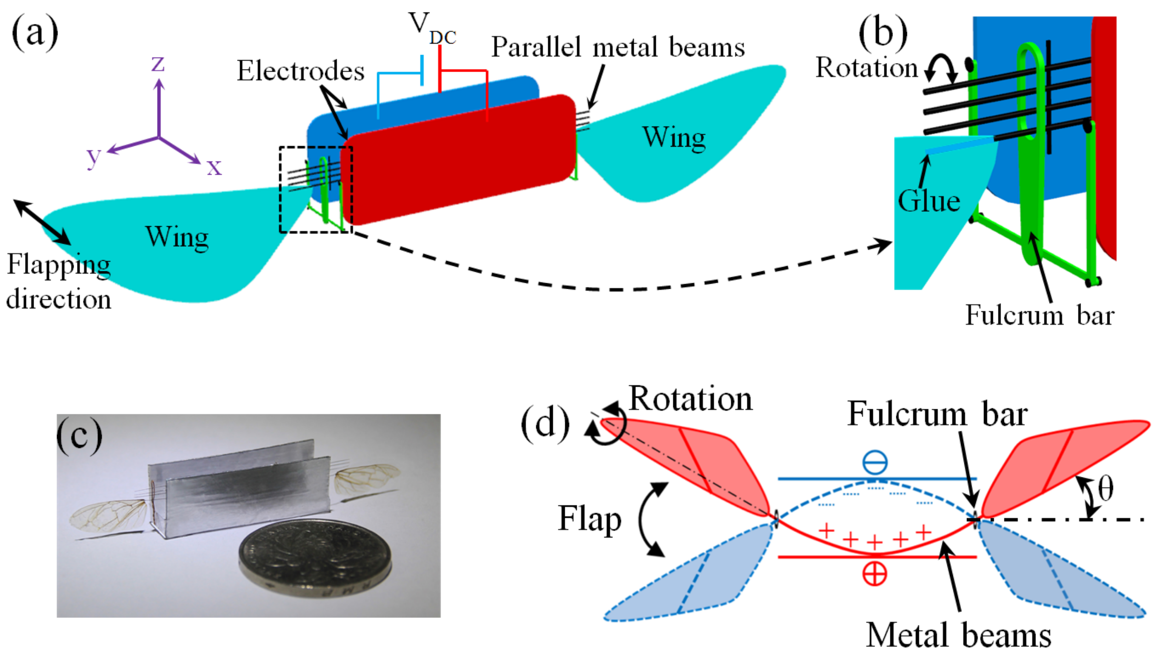

Figure 1: (a) Configuration of the actuator. (b) Detailed structure of the flapping wing assembly. (c) Photo of the actuator and a coin. (d) Top view of the flapping wing assembly in self-resonance state under the electrostatic actuation. Red and blue color configurations are two different states when beams are in contact with the negative and positive electrodes, respectively. In additional to the lateral flapping movements, the wings also have rotational motion to provide the lift force.

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DESIGN

Figure 1a shows the configuration of the actuator, which consists of four parallel metal beams, two wings, two fulcrum bars and two electrodes. The parallel metal beams together with the two wings (as a flapping wing assembly) are placed in the middle of the two electrodes, and hold by the two fulcrum bars with oval holes. The electrodes are simply connected to a DC power source. Fig. 1b is the detailed assembly drawing, which shows that the two wings are glued at both ends of the lowest beam. A prototype device has been fabricated as shown in Fig. 1c, where the beams are made of metal alloy wires with length of 27mm and diameter of 60μm, and the wings are extracted from drone honey bees with the size of 12 mm in length and 5 mm in width.

It is noted that, the multiple beams, rather than a beam or a flat plate, are designed to enhance the electrostatic driving force and meanwhile reduce the air damping force. The oval holes on the fulcrum bars provide suitable support to the flapping wing assembly while allowing it to rotate around y-axis (the beam direction, Fig. 1b). The wings are only glued to the lowest beam for the purpose of inducing the wing rotation, which will be explained later in the next section.

The working principle of the actuator can be illustrated in Fig. 1d. When a DC voltage (V_{DC}) is applied, a steady electrostatic field will be generated between the two electrodes. Due to electrostatic induction effect, the electrostatic force will act on the parallel metal beams, and attract the beams toward one of the electrodes. With the increase of V_{DC}, the beams will move further until V_{DC} reaches the pull-in voltage, under which the beams can touch the positive electrode (red color) and get charged. Afterwards, the charges with the same polarity repel each other and the electrostatic force will drive the beams to the opposite electrode - the negative electrode (blue color) and release the charges. Subsequently, the beams can be excited into a resonance state at their natural frequency through impacting the positive and negative electrodes alternately, and thus actuate the two wings into cyclic motions. During the resonance, the charge and discharge processes generate a series of pulse currents going through the circuit, which can be measured by connecting a resistor together with an oscilloscope in series. The pulse currents also can be used to obtain the resonant frequency and power consumption of the actuator [7, 8]. Under current prototype design, the typical resonant frequency is 50-70Hz, and the typical power consumption is 6-10mW.

It is noted that, the actuator is subjected to a static DC voltage, and its alternating driving force is generated and sustained by its self-resonance. From the view point of structural dynamics, the actuator actually undergoes a "self-exited vibration", which is similar to asynchronous motions of insect flight muscles [9]. While conventional actuators usually operate at a "force vibration" state, which needs complex AC circuits to generate, sense and feedback for the control of sustained resonance. The actuation scheme presented here is more aligned with the bionic actuation as compared with other conventional actuators.

PERFORMANCE TESTS

Both wing motion and lift force measurements have been conducted quantitatively in order to investigate the actuator's characteristics and explore the possibility for applications in artificial flying insects. A test system has been designed as shown in Fig. 2a, which consists of a

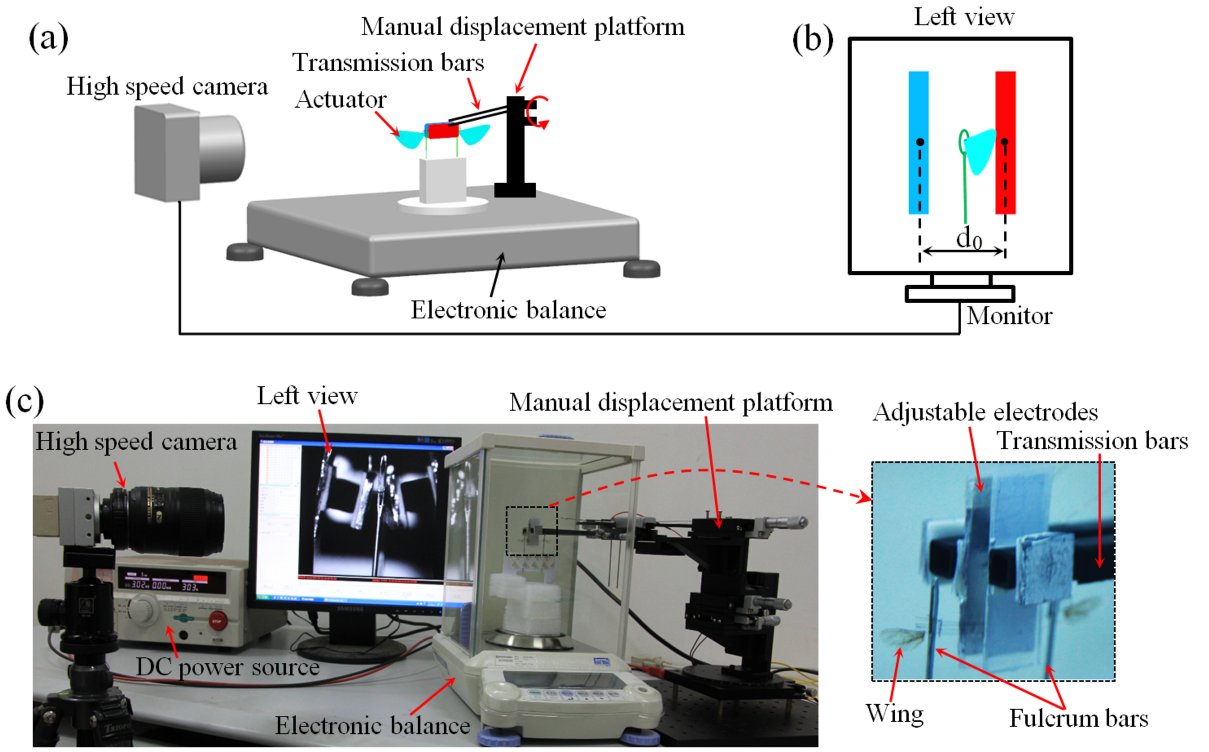

Figure 2: Test system of the actuator for wing motion and lift force measurements. (a) Measurement scheme. (b) A monitor showing left view of the actuator. (c) Photo of the whole test system.

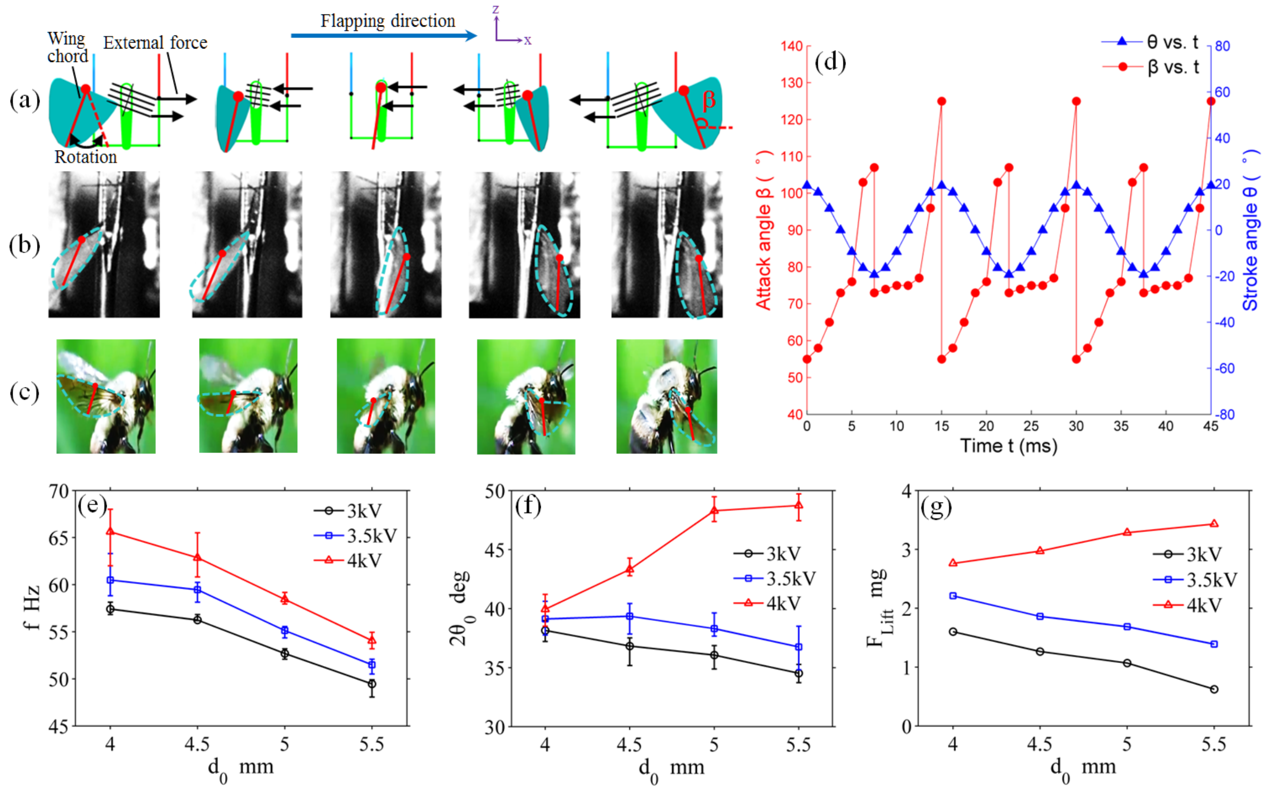

Figure 3: Step-by-step operations of the actuator in (a) illustrations and (b) high-speed experimental photos (d_0 = 4mm, V_{DC} = 4kV). (c) High-speed photos for wing motion of a real honey bee. (d) Stroke and attack angles of the wing during the vibration with frequency of 66.7Hz (d_0 = 4mm, V_{DC} = 4kV). Experimental measurements of (e) vibration frequency, (f) amplitude, and (g) lift force with respect to the input DC voltage (V_{DC}) and the gap distance (d_0).

manual displacement platform with two transmission bars, a high speed camera and an electronic balance. The actuator's electrode gap distance d_0 can be adjusted by the manual displacement platform through the transmission bars. Its wing motion can be captured by the high speed camera from the left view (Fig. 2b). And its average lift force can be measured based on the reduced weight readings on the electronic balance. Fig. 2c shows the photo of the whole test system.

Figure 3 shows the step-by-step operations of the flapping wing assembly in schematic illustrations (Fig. 3a) and photos taken by the high speed camera (Fig. 3b), which are directly compared with real insect wings in operation (Fig. 3c). In these images, the red solid lines represent the wing chord and β is the wing's attack angle. Since only the lowest beam is glued with the wings, the external force (resultant of electrostatic and air damping force) is different from other beams, which will make the lowest beam to vibrate out of phase and thus cause a rotation around y-axis up to 50 º in the prototype device. The rotational motion has been proven to be key factor to generate high lift force in real insects [10]. While in the previously artificial flying insects, the rotational motion is realized through the passive deformation of an elastic wing hinge, which is usually subjected to short endurance due to fatigue problems [3, 5].

Fig. 3d plots the wing's stroke (θ, Fig. 1d) and attack angle (β, Fig. 3a) vs. time for several periods, which reveals that the wing is undergoing reciprocation at sinusoidal regime with stroke frequency of 66.7Hz, and stroke amplitude of 38.49° (peak-to-peak). Figures 3e–3g record the stroke frequency (f), amplitude ($2\theta_0$), and lift force (F_{Lift}) under various electrode gap distances (d_0) and DC voltages (V_{DC}). It can be observed that, larger gap distance is beneficial to generating lift force in these tests, and higher DC voltages are required to sustain the higher flapping frequencies and amplitudes. These characteristics may be used for lift force optimization and flight attitude control in the future.

TAKEOFF TESTS

In order to demonstrate the self-lifting capability of the actuator, we have designed a vertical takeoff system based on the prototype device. As shown in Fig. 4a, the flapping wing assembly is supported by two long U-shape rails instead of the two fulcrum bars (Fig. 1b), and the electrodes are extended to give the wing assembly continuous electrostatic forces. These changes will allow the wing assembly to move upward along the U-shape rails if there is enough lift force generated by the flapping wings.

Test results show that, successful takeoffs have been achieved and recorded in video clips as shown in Fig. 4b, which illustrates that the flapping wing assembly (3.1mg in weight) is self-lifted 5cm above the ground once a V_{DC} of 5kV is applied. The lifting height is limited by the current experimental setup and can be further increased through extending the U-shape rails and electrodes.

As a comparison, same tests are also conducted for a metal beam assembly with no wings (no lift force). As

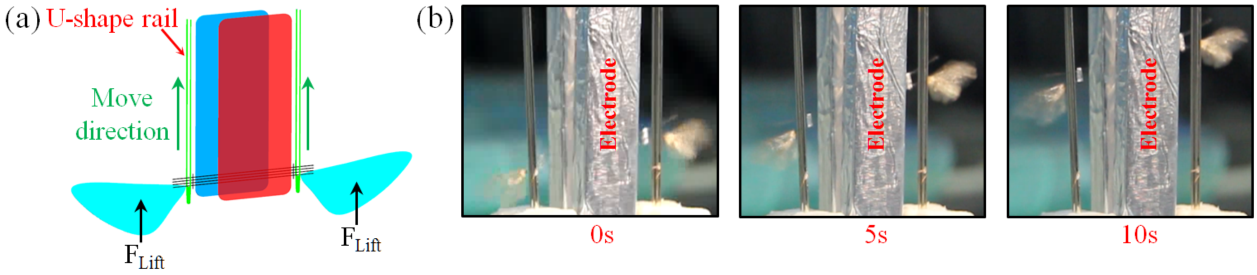

Figure 4: Vertical takeoff system for flapping wing assembly utilizing the electrostatic force. (a) Schematic view of the takeoff system. (b) Visual demonstration of the takeoff of the flapping wings with vibration frequency of 70Hz, and upward speed of 2.2mm/s. (Gap distance d = 5mm, V_{DC} = 5kV).

expected, without the wing structure, the assembly can't achieve vertical takeoff. The comparison tests demonstrate that it is the lift force generated by the flapping wings, not the climbing effect presented in previous references [11], results in the hovering of the flapping wing assembly. The successful takeoffs make the actuator promising in the area of micro-flying robots, where weight and size limits are major concerns.

CONCLUSIONS

This paper presents a self-excited electrostatic actuator with a simple construction and operation procedure, which can be excited into resonance under DC power source without using complex AC driving circuits. The actuator can drive two insect wings into reciprocation with rotational motion and thus generate effective lift force high enough to result in self-lifting of the flapping wing assembly. The wing motion and lift force measurements as well as takeoff tests in this paper demonstrate the feasibility of using this new actuator in flapping-wing robots. Our next work aims at further enhancing the lift force and reducing the total weight, for the purpose of realizing the takeoff of the whole actuator.

ACKNOWLEDGEMENTS

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