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
Insect-scale flapping-wing robots can be considered as Micro Air Vehicles (MAVs) with wingspans of less than 3-5cm with 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 (including frequency, amplitude and trajectory etc.) with desirable simple designs and low weight. The biomimetic wing motion is the key to generate the lift force, and the structural design is vital for autonomous lift and 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 insect-scale flapping robots, 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 [2] as the moving electrodes were not able to imitate the “rotational” flapping motions of insect wings.

In 2013, an insect-scale flapping-wing robot has been demonstrated using piezoelectric flight muscles [3]. Here, we demonstrate the first vertical lift motions of artificial insect wings via electrostatic flapping actuators [7]. The actuator can work at the 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 is designed and fabricated for the purpose of investigating 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 fixed electrodes to get and release charges, respectively. In additional to the lateral flapping movements, the wings also have rotational motion to provide the lift force.
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 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 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 parallel metal beams are made of metal alloy wires with length of 27mm and diameter of 60 μm, 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 (Fig. 1b). The wings are only glued to the lowest beam for the purpose of inducing the wing’s rotational motion around the beam direction (y-axis), 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 to record 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 motion of insects’ flight muscles [9]. While conventional actuators usually operate at a “force vibration” state and need complex AC circuitry 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](image_url)

*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.*
manual displacement platform with two transmission bars, a high speed camera and an electronic balance. The actuator’s gap distance \( d_0 \) between the two electrodes 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 high speed camera (Fig. 3b), which are directly compared with a real insect’s wing in operation (Fig. 3c). In these images, the red solid lines represent the wing chord and \( \beta \) 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 rotational motion along \( y \)-axis up to 40° 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 attempted flapping-wing robots, 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 (\( \theta \), Fig. 1d) and attack angle (\( \beta \), Fig. 4a) vs. time for several periods, which reveals that the wing is undergoing reciprocation at sinusoidal regime with stroke amplitude of 38.49° (peak-to-peak) and flapping frequency of 66.7Hz. Figures 3e–3g record the flapping frequency of the prototype device (f), amplitude (2\( \theta_0 \)), and lift force (\( F_{\text{Lift}} \)) under various electrode gap distances (\( d_0 \)) and DC voltages (\( V_{\text{DC}} \)). It can be observed that, larger gap distance is beneficial to generate lift force in these tests, but 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 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 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 \( V_{\text{DC}} \) of 5kV is applied. As a comparison, same tests are also conducted for a metal beam assembly with no wings (no lift force). As expected, without the wing structure, the assembly can’t achieve vertical takeoff. This comparison test demonstrates 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 and transmission mechanisms. The actuator can drive two insect wings into reciprocation with rotational motion and thus generate effective lift force high enough to result in self-takeoff of the whole assembly. The wing motion and lift force measurements as well as takeoff test 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.

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REFERENCES


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