LATERAL MOVING OF AN ARTIFICIAL FLAPPING-WING INSECT DRIVEN BY LOW VOLTAGE ELECTROMAGNETIC ACTUATOR

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ABSTRACT

We present an artificial flapping-wing insect driven by a low voltage electromagnetic actuator to move laterally along a horizontal guide rail for the first time. Three distinctive achievements have been accomplished: (1) only 90mg in weight with wing span of 3cm for the prototype; (2) high peak to peak flapping amplitude of 100.4° at 51.3Hz under a low driving voltage of 5V; and (3) measured 116.5 μN average lift force to move the prototype on a horizontal guide rail. As such, this work opens a new class of drive methodology for artificial flapping-wing insects.

INTRODUCTION

Over the past decade, artificial flapping-wing insect with wing span less than 5cm has set off a new wave of research in pursuit of high efficiency, maneuverability and agility of real insects in nature [1]. Considering the low weight budget and stringent size limitation, the crucial step in designing an artificial flapping-wing insect is choosing a suitable actuator with simple structure and high power density in centimeter or even in millimeter scale. The output motion of the actuator should be easily transformed into the flapping motion of the artificial wings and driving voltage of the actuator should be acceptable as high voltage requires indispensable booster circuit, which causes extra weight to the system [2]. Therefore, at present it is still challenging for the actuators to meet the requirements for artificial flapping-wing insect's autonomous flight.

Among the existing actuators designed for artificial flapping-wing insects, conventional motor [3, 4] is a typical form with low driving voltage and high output power. However, when the wing span decreases to centimeter scale, conventional motor suffers greatly in efficiency due to size effects and structural complexity caused by additional crank rocker mechanism used for motion transmission [1]. To fill in the blanks of actuation in centimeter or millimeter scale, piezoelectric [5, 6] and electrostatic actuators [7, 8] have been adopted as alternative actuation options. Although these actuators can achieve flapping motion with much simpler structure, they all require high operating voltage (hundreds of volts for piezoelectric and thousands of volts for electrostatic actuator), which makes booster circuits indispensable to the system. Given that, actuators with both simple structure and low driving voltage [9] are more preferred in developing artificial flapping-wing insect.

In this investigation, we report a centimeter scale artificial flapping-wing insect driven by a low voltage electromagnetic actuator. The actuator can operate under a voltage of a few volts and drive the artificial wings with large amplitude through a simple transmission mechanism. To investigate the output performance of the artificial flapping-wing insect, a prototype is fabricated and its wing motion and lift force are tested. In addition, to visually demonstrate the effective lift force, a horizontal guide rail is designed and lateral moving of the prototype is observed. In contrast to prior works in piezoelectric actuators [5, 6] or electrostatic actuators[7, 8], the electromagnetic actuator presented in this investigation proposes a new driving option for artificial flapping-wing insect with much lower driving voltages.

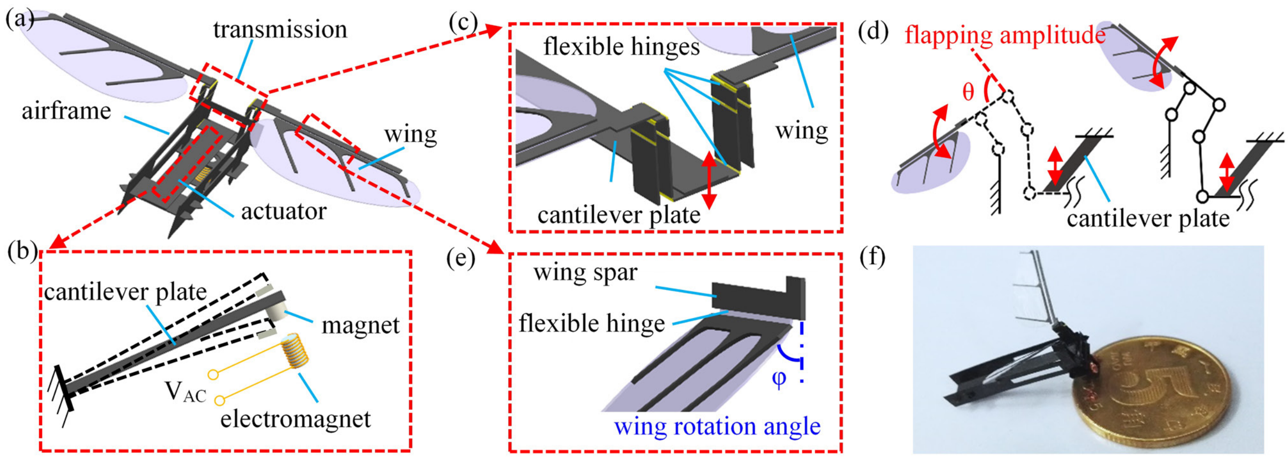

Figure 1: (a) Configuration of the artificial flapping-wing insect. (b) Schematic diagram of the electromagnetic actuator. (c) Enlarged view of the flexible hinges used in transmission. (d) Schematic diagram of the transmission to illustrate its working principle. (e) Enlarged view of the wing rotation achieved by using flexible hinge. (f) Optical photo of an artificial flapping-wing insect prototype with a 50-cent coin.

DESIGN

Figure 1a presents the overall view of the artificial flapping-wing insect and its main components, which consist of an electromagnetic actuator, a set of transmission mechanism, two artificial wings and an airframe. The actuator outputs vibratory motion to drive the artificial wings for lift force through transmission mechanism and the airframe provides structural support for the whole system. Figure 1f shows a photo of the artificial flapping-wing insect prototype beside a 50-cent coin to illustrate scale.

Figure 1b illustrates the working principle of the electromagnetic actuator. The actuator consists of a permanent magnet, a cantilever plate and an electromagnet. The permanent magnet is glued to free end of the cantilever plate and the electromagnet is set below the permanent magnet. When the driving frequency of the AC electromagnet matches the first-order natural frequency of the cantilever system (including cantilever plate and permanent magnet), the cantilever plate can be excited into resonance to output vibratory motion.

To magnify the small vibratory motion into flapping motion with large amplitude, a set of transmission based on the principle proposed by "Robot Bee" in Harvard University [10] is integrated to the system. Figure 1c illustrates the schematic diagram of the transmission by using flexible hinges as turning joint and Figure 1d illustrates its working principle. When the cantilever plate in the actuator is excited into resonance, it pulls and pushes the transmission mechanism up and down as shown in Figure 1d. Since the artificial wing is mounted to the transmission through flexible hinges, its motion can be magnified further based on the leverage principle and thus forms a large and reciprocating flapping amplitude.

During flapping flight, wing rotation is indispensable in wing flapping sequence for high lift force. As shown in Figure 1e, a flexible hinge is also used between the wing and wing spar to achieve effective wing rotation angle.

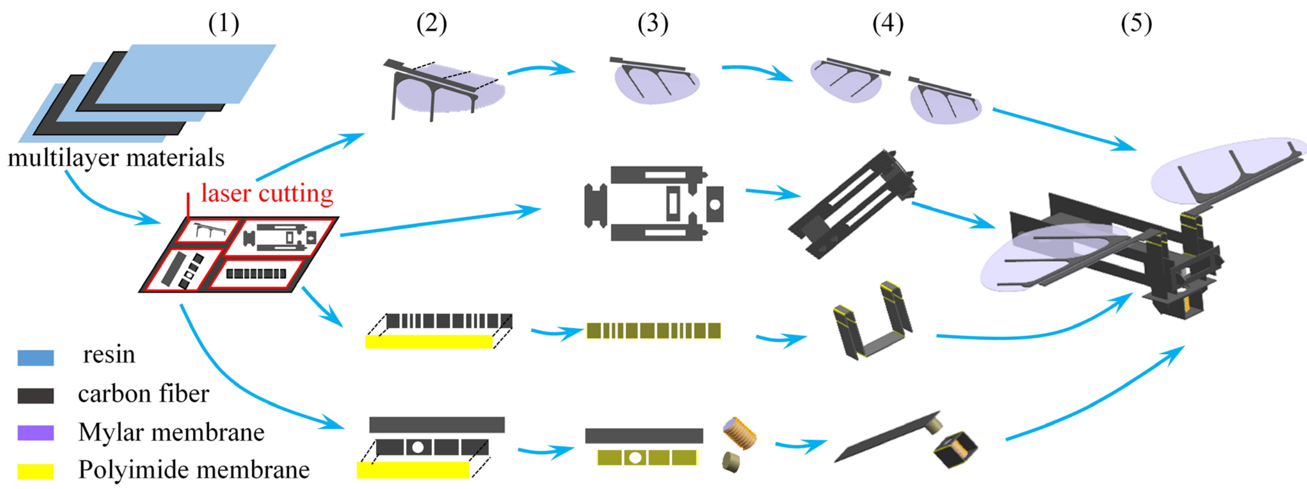

Figure 2: Fabrication procedures of the artificial flapping-wing insect prototype.

FABRICATION

Considering the small size and light weight of the artificial flapping-wing insect of this investigation, material selection and fabrication processing is vital important to its performance. Figure 2 illustrates the fabrication procedures of the artificial flapping-wing insect prototype.

For the artificial wings, two layers of carbon fiber sheets (30μm-thick) are firstly glued to each other by epoxy resin. The angle between the two layers of carbon fiber sheets is determined by the venation pattern of the artificial wings. Then the wing venation is cut from the carbon fiber based multilayer structure by high precision laser cutting technique. The same technique is used to cut the wing membrane from thin Mylar (2.5μm-thick). After that, these two parts are cured in high temperature and epoxy resin solidifies to form a strong bonding of the multilayer structures. During the curing process, an additional weight is put on the wing surface to prevent warpage.

For the airframe, several small parts are firstly cut from the carbon fiber sheet by using laser cutting technique. After they are cured and solidified, these small parts are assembled through mounting flanges and grooves. Super glue is also used at the mounting groove to prevent loosening.

For transmission and holder of the electromagnet, the fabrication procedure is same as that of the artificial wings. When the four major components are fabricated completely, they are assembled to form an artificial flapping-wing insect prototype with wing span of 3cm and weight of 90mg. Table 1 gives the mass of each component.

Table 1: Masses of the 4 major components.

Component	**Mass** (mg)
Actuator	65.8
Wings	1.4
Transmission	5.6
Airframe	13.7
Glue	3.5
Total	**90**

WING MOTION

During flapping flight, wing flapping amplitude and time varying wing rotation angle are two key parameters which determine the lift force. In this investigation, a high speed camera is utilized to capture the three dimensional wing motion from different angles separately. Figure 3 illustrates the schematic diagram of the test system. To capture wing rotation movements, a high speed camera is set at side view of the prototype. To measure the flapping amplitude, the high speed camera is located at top view of the prototype.

Figure 4 shows the step by step operation of the wing flapping amplitude and wing rotation movement. During the test, the sampling frequency is set at 1000 frames per second. Under a driving voltage of 5V, the prototype produces 100.4° peak to peak flapping amplitude at 51.3 Hz. By using the flexible hinge, effective wing rotation pattern is achieved during lateral flapping. The maximum wing rotation angle can reach 50° during the rotation process. Considering the wing rotation angle is mainly caused by aerodynamic loads on the wing surface and the actuator has no active control over the process, the captured wing rotation movement fits well with the "passive wing rotation" pattern [10], which is widely adopted in artificial flapping-wing insect design and real insects in nature.

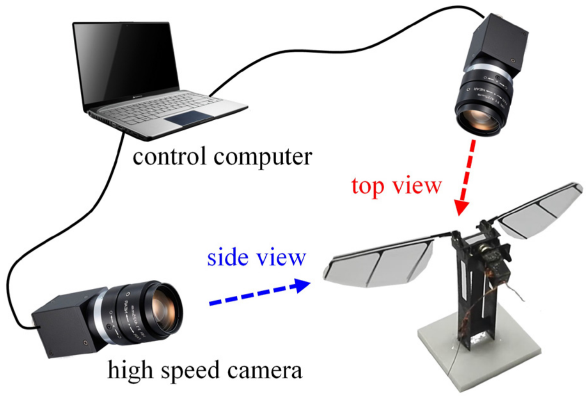

Figure 3: The test system to capture the three dimensional wing motion by setting the high speed camera at different angles.

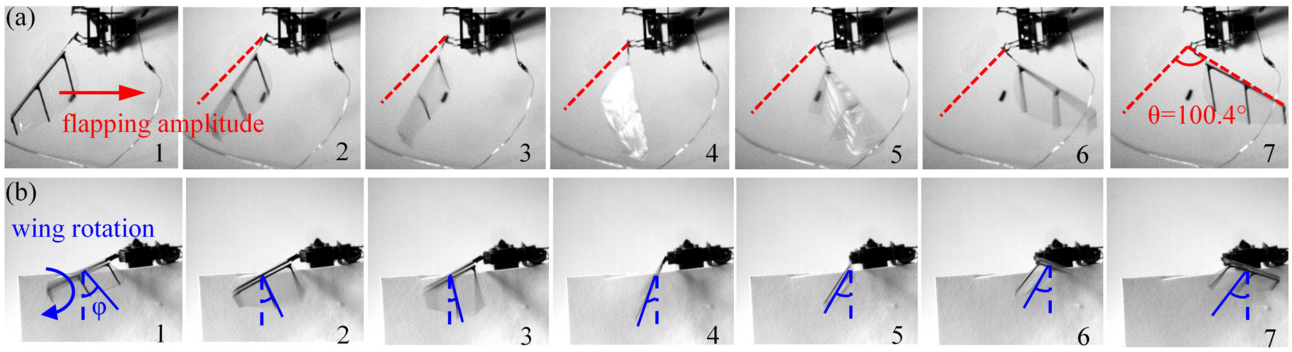

Figure 4: Step by step wing flapping amplitude and wing rotation photos captured by the high speed camera.

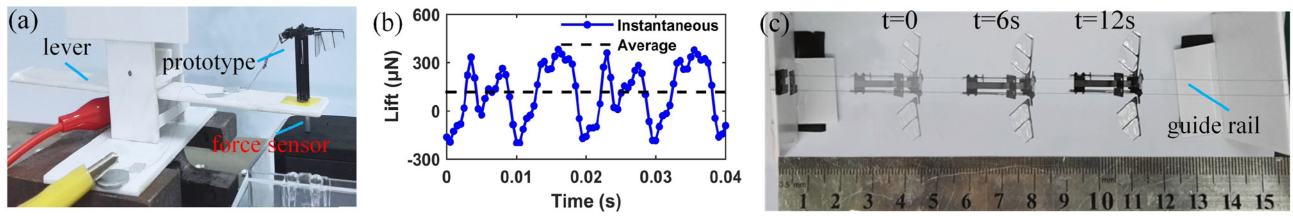

Figure 5: (a) The lift force test platform using a force sensor and a lever. (b) Measured instantaneous lift force in two cycles. (c) The lateral moving of the prototype along a horizontal guide rail.

LIFT FORCE

To investigate the aerodynamic performance of the presented artificial flapping-wing insect, a test platform capable of obtaining instantaneous lift force is designed. As shown in Figure 5a, the test platform uses a lever to ensure the probe of the force sensor is under compression during the test [7]. Therefore, the lift force measurement is constrained to a single degree of freedom along the vertical direction. To reduce the influence of external vibration from the environment, the test platform is set on a vibration isolated table.

Figure 5b presents the instantaneous lift force in 2 cycles measured by the test platform at a sampling frequency of 2000Hz. Under a driving voltage of 5V, an average lift force at 116.5μN is generated by the prototype at a flapping frequency of 51.3Hz. Since the wings go through lateral flapping amplitude twice in one cycle, two major peaks in one cycle are also observed in the time varying lift force.

To demonstrate the lift force visually, a horizontal guide rail made of two parallel Ni-Ti wires are designed and the prototype is hung on the rail as shown in Figure 5c. When the AC voltage is applied, the prototype moves from the left side to the right side at a velocity of 0.5cm/s.

CONCLUSION

This paper presents an artificial flapping-wing insect driven by a low voltage electromagnetic actuator. The actuator outputs vibratory motion to drive the artificial wings through a set of transmission mechanism. Under a driving voltage of 5V, the artificial flapping-wing insect prototype produces 100.4° peak to peak flapping amplitude at 51.3 Hz and the maximum wing rotation angle can reach 50° during the wing rotation process. Such wing motion leads to an average lift force of 116.5μN and the lateral moving of the prototype along a horizontal guide rail. Future works aim at further enhancing the aerodynamic lift force by achieving higher flapping frequency and more reasonable combination of wing flapping and rotation movement.

ACKNOWLEDGEMENTS

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