Asynchronous and Self-Adaptive Flight Assembly via Electrostatic Actuation of Flapping Wings

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About three quarters of flying insects on Earth use the asynchronous driving mechanism in muscles to power their flights. Herein, an asynchronous flight assembly via electrostatic actuation of flapping wings in analogy to the asynchronous mechanism in natural flying insects is demonstrated. The wing motions are driven by the self-sustained oscillation of metal beams in a steady electric field and regulated by the input voltage between two stationary electrodes, whereas the discharging process occurs repetitively as the oscillating beams hit and exchange charges with the electrodes. Several advancements in the oscillation and flight demonstrations have been achieved: 1) self-sustainable and asynchronous oscillations for biomimetic flapping-wing motions with high efficiency, 2) the first takeoff of an asynchronous flight assembly along the fixed electrodes, and 3) the first self-adaptive hovering assembly via the passive modulation of the flapping frequency and amplitude when a disturbance is introduced.

1. Introduction

Nature has been the inspiration in the history of technological advancements.[1-8] For example, flying insects are capable of producing rapid flapping motions[9,10] to power their flights with good efficiency.[1,11] Lessons and techniques derived from these flying mechanisms could be beneficial for the development of miniaturized flying robots. Specifically, two types of flight muscles are generally found in nature: the synchronous flight muscles with synchronous motions under the 1:1 “neurogenic” control, typically found in large species,[12-14] and the asynchronous flight muscles with the asynchronous motions under the 1:N “myogenic” control,[15,16] typically seen in approximately three quarters of the flying insects.[16]

For the synchronous flight muscles, each contraction or relaxation is initiated by a neural impulse coupled with closed-loop controls. To achieve sustained flapping motions and stable flights, natural insects can regulate the flapping behaviors (frequency, amplitude, etc.) of wings through the neural system to adjust the lift forces and eliminate the asymmetric aerodynamics of wings.[13,15] Researchers have concentrated on the synchronous driving mechanism for the state-of-art flying robots and soft robots in the literature by sensing and controlling the wing motions with several different actuation schemes, including electrostatic,[17,18] piezoelectric,[1,19-21] electromagnetic,[22-25] and dielectric elastomer[26] actuators, DC motors,[27,28] as well as artificial muscles.[29,30]

In contrast, the asynchronous flight muscles maintain the contraction and relaxation activities based on the stretch-activation mechanism, which is a self-oscillatory mechanism,[15] under the stimulation of one neural impulse.[13,31] The flapping behavior of wings in each cycle depends on the inherent characteristics of the muscle-wing structure rather than the neural system. Figure 1a,b shows the natural asynchronous flight muscles with 1:N myogenic action and four-steps electrophysiology procedures.[15,12,13] In the biological structure, two sets of muscles (muscle #a and #b in Figure 1b) are responsible for the up and down strokes through the thorax. The myogenic actions can induce the two muscles to contract out of phase (alternatively) with a frequency typically higher than that of the neural input impulses[16,34,35] for the oscillatory motions. Specifically, when muscle #a contracts actively, muscle #b can be stretched by
muscle \#a (passively stretch). Afterward, muscle \#b will contract actively due to the stretch-activation mechanism and cause muscle \#a to passively stretch. The process continues for the muscles to contract and stretch alternatively and autonomously. Figure 1a shows that four steps of electrophysiology procedures are needed to maintain the 1:N myogenic actions:\[36,37\] 1) a neural impulse is sent to release calcium ions (Ca\(^{2+}\)) from the sarcoplasmic reticulum (SR) to cytoplasm where there are many sarcomeres to maintain a tonic level of calcium; 2) the calcium ions can attach to the troponins of sarcomeres to build up an ATP-dependent “cross-bridge” between the myosin and actin filaments; 3) the cross-bridge can shrink the sarcomeres and activate the pair of muscles to contract alternatively and autonomously to achieve continuous oscillations; and 4) over time, the calcium ions are pumped back to SR after consuming ATPs in the mitochondria while the self-oscillatory motions stop until another neural input impulse is generated to release more calcium ions. As a result, one neural impulse can add calcium ions\[38\] to result in many oscillatory motions for the “self-oscillatory” behavior.\[16\]

The unique myogenic mechanism and compact biological structure of the asynchronous flight muscles result in better performances (e.g., energy consumption and efficiency) for flying insects.\[18\] However, this natural strategy has never been fully explored for artificial flying robots.

Here, we investigate the artificial asynchronous flight muscle via electrostatic actuation of flapping wings, as shown in Figure 1c,d, to mimic the 1:N myogenic action with calcium ion regulation (in the natural muscle). As shown in Figure 1c, the asynchronous flight muscle has a compact structure with conductive and moving beams. Using a direct current (DC) voltage source\[18,39,40\] similar to that of a single neural impulse in natural flying insects, self-sustained oscillations of a variety of conductive materials (super-elastic shape memory alloy (SMA) and so on) can be induced in a steady electric field without any AC (alternating current) power source. The electrons in this approach play a role similar to the calcium ions in the biological mechanism to regulate the oscillations. As electrons gradually dissipated, the self-oscillatory motion stops until another voltage impulse is applied and the overall sequence is similar to that of the natural asynchronous flight muscle, where calcium ions are used to maintain the self-oscillatory motions. In summary, the self-sustained oscillation and stretch-activation mechanism both provide the mechanism by which electrical impulse or ATP becomes converted into mechanical energy and movement.\[41\] In contrast with synchronous actuation (piezoelectric, electromagnetic, etc.), self-sustained oscillation has the advantages of high efficiency, free of AC circuit, and ease of miniaturization.\[42\] Experimentally, guided takeoff and self-adaptive hovering are achieved by the flight assembly, which set important milestones for robotic flying insects. Three ground testing prototypes with 25.4–2.9 mg in weight are designed and fabricated to study the effects of miniaturization with detailed analyses on the performance variations.

**Figure 1.** Illustrations of both the natural and artificial asynchronous flight operations. a) 4 steps of the electrophysiology procedures in the natural asynchronous flight muscles.\[15,32,33\] b) The 1:N myogenic actions for the natural muscles showing one single impulse can induce many cycles of wing beats for Sarcophaga Bullata.\[34\] c) The 1:N electrostatic actuation for the artificial asynchronous flight muscle showing one single charge can induce many cycles of wing beats. d) Four steps of electronic procedures of the artificial asynchronous flight muscle. e) The Franklin chimes powered by lightning. f) Measured voltage versus time sequences on the electrode (for intervals of 0.5–0.9; 1.5–1.9; and 2.5–2.9 s) showing the duration of the asynchronous motions of a prototype after one electrical impulse is applied by a 1.67 kV, 1.3 nf capacitor (see details in Figure S1, Supporting Information).
2. Results

2.1. Concept of the Artificial Asynchronous Flight Muscle

Figure 1d shows the sequence of the artificial asynchronous mechanism in four steps in analogy to the electrophysiology procedures of the natural muscle: 1) an electrical impulse from a voltage source is applied to the fixed electrodes through a switch to supply a large number of electrons (e⁻) at the negative electrode (marked as NE), and to establish a steady electric field. The electrostatic force causes the movements of the metal beam to hit the negative electrode, which will subsequently release some electrons to the beam. 2) The released electrons are attached to the surface of the beam to negatively charge the beam. 3) The negatively charged beam is repelled by the NE and attracted by the electrostatic force to impact the positive electrode (marked as PE), and is positively charged. This impact and charge processes can continue back and forth as long as there are sufficient charges. 4) Over time, the oscillation stops due to the consumption of charges which lowers the electrical potential and another electrical impulse is required to start the motion again. This working sequence is inspired by the historical Franklin chimes powered by lightning, as shown in Figure 1e,[43,44] Figure 1f shows measured voltage variations of a sampling resistor in a prototype system with respect to time using the test setup, as shown in Figure S1, Supporting Information. The overall duration of the oscillation under a single impulse varies from 0.192 to 8.252 s depending on the capacity of the tested capacitors between 0.1 and 4.2 nF as detailed in Table S1, Supporting Information. The impact process between the beam and the electrode is rather complex such that the recorded voltage amplitude is chaotic at each contact. However, it is found that both the absolute voltage value and impact frequency reduce gradually over time as the charges are consumed in the process. Furthermore, only a single impulse is needed to induce and sustain the oscillatory movements by providing charges to the fixed electrodes, this “self-sustained oscillation” is similar to the 1:N myogenic action of the natural asynchronous flight mechanism, as shown in Table 1. From the viewpoint of structural dynamics, a structural resonant oscillation can be realized in two ways: 1) a continuous actuation via the synchronous control where the oscillation frequency and amplitude are governed by the control signals; and 2) a continuous actuation without the synchronous control where the oscillation frequency and amplitude are mainly governed by the structural characteristics. The former is usually used by other works in the robotic flying insects, and the latter is used by this work as well as about three-quarters of all-natural flying insects on Earth.

2.2. The First Takeoff of the Asynchronous Flight Assembly

As shown in Figure 2, an asynchronous flight assembly is designed, fabricated, and tested based on the concept of artificial asynchronous flight muscle. The asynchronous flight assembly includes four metal beams and two wings for a total mass of 5.4 mg. Based on laser cutting of thin plastic films, the flight assembly can be fully made by artificial materials without using wings from natural bees.[45] Figure 2b shows the fabrication and assembly process of the flight assembly, which has three components, including the wing veins, wing membrane, parallel metal beams connected in series as the flight muscles. The wing veins with the size of 10 mm in length and 5 mm in width are made of 30 μm-thick unidirectional prepreg tapes based on carbon fiber from Zoltek and the wing membranes are made of 3 μm-thick polyimide films from Polyktech. The parallel metal beams with a diameter of 60 μm are made of four superelastic Ni-Ti alloy wires from Menny. The multiple-beam design, rather than a single beam or a flat plate design, helps to increase the electrostatic driving force without inducing strong air damping. It is noted that as only the lowest beam is glued with the wings, the external force (resultant of electrostatic and air damping force) is different for the lowest beam to vibrate out of phase with other beams and to induce a rotational motion along the γ-axis, so this design is an active wing rotation case.

To verify the flight assembly can generate enough lift force to take off, a hovering testing prototype is designed, which includes the flight assembly, U-shape rails, and two fixed electrodes (Figure 2a). When the metal beams are oscillating between the fixed electrodes, the artificial wings can be actuated to complete the flapping motion. Experiments show that the flight assembly (Figure 2b) can generate a high enough lift force to fly upward along the rails (Figure 2c). Both the takeoff and hovering of the flight assembly have been achieved and recorded (see Movie 1, Supporting Information). The rolling rotation (right wing went up and the left wing went down) is due to the difference of lift force generated by the two wings due to the differences in fabrication and assembly processes.

2.3. Self-Adaptive Hovering Demonstration

In the natural world, flying insects may experience various disturbances in their flight. For example, the flying mosquitoes may

Table 1. Analogy between the natural and artificial asynchronous flight mechanisms.

| Mechanism | Electrophysiology of the natural muscle (1:N myogenic action) | Electrostatics of the artificial muscle (1:N electrostatic actuation) |
|-----------|-------------------------------------------------------------|---------------------------------------------------------------|
| Step #0   | A neural impulse is applied to maintain the Ca²⁺ level      | An electrical impulse is applied to maintain the e⁻ level     |
| Step #1   | Ca²⁺ are released by sarcoplasmic reticulum (SR)            | e⁻ are released by the negative electrode (NE)                |
| Step #2   | Ca²⁺ are attached to the troponin of sarcomere              | e⁻ are attached to the surface of the beam                     |
| Step #3   | Sarcomeres are shrunk after stretch                         | Beam is deformed after impact                                 |
| Step #4   | Ca²⁺ are pumped back to SR after N cycles                   | e⁻ are dissipated to PE after N cycles                        |
be hit by the falling raindrops,[46] and foraging bees strike their wings against leaves and flower petals roughly once per second when weaving through cluttered vegetation in search of floral resources.[47] However, in many cases, the flying insects will exhibit passive self-adaptive characteristics to external disturbances so that there is no fundamental damage to their flight.[48]

In our work, test results indicate that the flight assembly also exhibits the unique feature of self-adaptive hovering. Two different types of disturbances are designed to simulate the daily flight environment of insects or flying robots and thus qualitatively examine the hovering stability of the flight assembly. As a result, the flight assembly shows passive modulation of both the flapping frequency and flapping amplitude to keep the total lift force roughly unchanged when an external disturbance is introduced to the flapping wings.

The first test for self-adaptive hovering is using water droplets to disturb the vibration of the right (or left) flapping wing temporarily. The test system is designed, as shown in Figure 3a, to demonstrate the impact of vertically falling water droplets to the flight assembly, water droplets squeezed out of the syringe drip on the rising flapping wing, the whole process is recorded by the highspeed cameras on the front, side and top of the device (see Movie 2, Supporting Information).

As shown in Movie 2, Supporting Information, the flight assembly has risen to the top of the guide rails before the water droplets fall. When the droplet drips onto the wing, the flight assembly is pushed downward a distance along the guide rails with a rolling angle (Figure 3b), which is similar to the mosquito surviving raindrop collisions with a rolling angle (Figure 3c).[46] This comparison indicates that a rolling angle is vital to minimize the momentum transfer for both mosquito and the flight assembly, although the latter is inclined before being impacted. Furthermore, a small amount of droplet remains on the flapping wing which causes the flapping amplitude of right wing to decrease. To compensate for the loss of lift force due to the decreased flapping amplitude, the flapping frequency increases from 70 to 90 Hz, as shown in Figure 3d. As the droplets are continuously thrown off the flapping wing, the flapping amplitude and flapping frequency of the wings gradually return to their original state, and the flight assembly returns to the top of the guide rails. It is noted that the time-varying trend of flapping frequency in our work is also in accordance with that of mosquitoes impacted by falling drops (see Movie 2, Supporting Information).

The experimental results can be explained as follows: 1) the input work done by the electric field force on the flight assembly during the moving process from one electrode to the opposite electrode is constant when the DC voltage and gap distance are unchanged. 2) A part of the input work is converted into the total kinetic energy of the flight assembly, whereas the other part is dissipated through the air damping of the wings. 3) When the droplets impact the right-wing, the amplitude of the right-wing greatly decreases, and the total damping work also decreases, so the kinetic energy imported to the flight assembly increases, as well as the velocity and the frequency of the flight assembly.

It is noted that the wings of insects are generally hydrophobic to prevent them from being knocked to the ground by raindrops, so the hydrophobic treatment of the polyimide films (wing membranes) can further enhance the flight assembly’s resistance to raindrop interference in future work.

To further demonstrate the lift force is roughly unchanged after external disturbances of the leaf, numerical simulations are carried out for instantaneous lift force. In the simulations, as the flapping and rotation angle are approximately varying sinusoidally, a quasisteady state aerodynamic model[49,50] is utilized to calculate the lift force (see Equation S1, Supporting Information), assuming that both the flapping angle and rotation angle vary sinusoidally.[19] Based on the time-varying wing flapping angle, rotation angle, and wing size, the instantaneous lift force and average lift force during the experiment are calculated (see Figure S2, Supporting Information). As shown in Figure 3e, the calculated average lift force of the flight assembly before disturbances is 40.67 μN. When the droplet first drips onto the right wing
wing, the calculated average lift force of two single wings are 5.09 and 35.13 μN and the total lift force is \(40.22\) μN.

Another self-adaptive hovering test is using a leaf (Figure 4b, Movie 3, Supporting Information) to disturb the vibration of the right (or left) flapping wing temporarily. During these disturbances, the amplitude of right wing reduces from 2.6 to 0.4 mm and the flapping frequency reduces from 77 to 65 Hz. However, the amplitude of left wing autonomously increases from 2.5 to 6.6 mm to compensate for the loss of lift force (Figure 4c). After the leaf is removed, the flight assembly can restore its flapping amplitude and frequency to the original values and return to the previous hovering state autonomously (Figure 4a).

The reason for the frequency decrease in the leaf disturbing experiment is the same as the water drop experiment: 1) the sum of the air damping work and kinetic energy should be unchanged. 2) After the amplitude of the right wing is limited by leaf, the amplitude of the left wing increases sharply, which causes the total damping work to increase, so the kinetic energy of the flight assembly decreases, as well as the velocity and frequency. In fact, the “self-adaptive” flight is achieved through the relationship between work and energy.

Similarly, the instantaneous lift force and average lift force during the experiment are calculated based on the test results of the flapping movement. As shown in Figure 4d, the calculated average lift forces before and after disturbances are 31.02 and 32.20 μN, respectively. The simulation results indicate that the average lift force of the flight assembly can be sustained even under the disturbances of the leaf, the reason is that even though the flapping frequency, amplitude, and lift force of right wing will be reduced by the leaf disturbing, the left wing can adaptively increase its flapping amplitude as well as lift force to compensate for the lost lift force of right wing.

To summarize, although due to the model error, the calculated lift force is less than the actual value, the lift force compensation mechanism is determined: both the flapping frequency and flapping amplitude of our flight assembly can be adjusted to keep the

**Figure 3.** Experiments and simulations of the droplets disturbing test (gap distance \(2d_0 = 4\) mm, \(V_{DC} = 4\) kV, wing length = 10 mm). a) Schematic of the droplet disturbing test. b) Step-by-step optical photos of deformed flight assembly eluding the falling droplet. c) Corresponding optical photos of a mosquito surviving raindrop collisions. Reproduced with permission. Copyright 2012, PNAS. d) Measured flapping frequency and amplitude of the wings during the droplets disturbing test (the spacing of observations in time is 1s). e) Simulation of the average lift force of the wings before and after disturbances.
lift force roughly unchanged under specific external disturbances. Furthermore, when the intensity of the external disturbance reaches a certain level, the flight assembly stops vibrating and the self-adaptive characteristic disappears.

For real insects, the amplitude and frequency of the wings are associated with energy expenditure in their muscle,[51] whereas for our self-adaptive experiments, the amplitude and frequency of the wings are depending on the input work done by electric field force on the flight assembly. It can be seen that the input work done by the electric field force in our prototype plays a role similar to the energy in the muscle in the biological mechanism of the real insects to regulate the amplitude and frequency.

2.4. Experiments and Simulations for Dynamic Characteristics at Different Sizes

To further study the dynamic characteristics of the asynchronous and self-adaptive flight assembly, ground testing prototypes are designed and fabricated. Different from the hovering testing prototype, the flight assembly in the ground testing prototype is fixed in the vertical direction for ease of wing motion and lift force measurement (see Figure S5, Supporting Information).

Figure 4. Experimental and simulation results of the leaf disturbing test (gap distance $2d_0 = 3.2$ mm, $V_{DC} = 3.75$ kV, wing length = 10 mm). a) Hovering state of the flight assembly before external disturbances. b) Hovering state of the flight assembly after external disturbances. c) Measured flapping frequency and amplitude (recorded by the highspeed camera, 500 fps). d) Comparison of average lift force before and after disturbances.

Figure 5a shows the physical structure of the first prototype (prototype #1a) consisting of a flight assembly, two electrodes, two fulcrum bars, and a ceramic capacitor. The electrodes consist of metal layers, electrode bases, and connection bars, where the metal layers are coated on the electrode bases. The flight assembly is supported by the fulcrum bars at both ends. The distance between the two fixed electrodes is denoted as $2d_0$, as shown in Figure 5b. Holes with the elliptical shape are designed on the two fulcrum bars to fix the flight assembly and allow the flapping motions along the x-axis and around the y-axis (rotation), as shown in Movie 4, Supporting Information. The fabrication and assembly process is shown in Figure S4, Supporting Information, and the details of materials, dimensions, and manufacturers of these components are shown in Table S3, Supporting Information. The wing length of flight assembly for three prototypes is from 5 to 12 mm (see Table S6, Supporting Information).

To sustain a stable long-term oscillation for testing, a series of impulses or a constant DC voltage of 2.4–4.0 kV should be applied to the electrodes. It is noted that, although the applied DC voltage is relatively high, the required input power of the prototype is less than that of current artificial flying robots due to the very small operating current (Figure S5c,
Figure 5. The ground testing prototype and experimental results (Prototype #1a). a) Overall structural configuration showing the flapping wing movements with the rotational component. b) Side view and c) top view of the biomimetic wings in motion. d) Step-by-step optical photos taken by a high-speed camera (3000 fps) from the side view for the first prototype \(2d_0 = 4 \text{ mm}, V_{\text{DC}} = 4 \text{ kV}\). e) Corresponding optical photos from a natural bee during flying operations. Reproduced with permission.\(^{[88]}\) Copyright 2009, UltraSlo. f) Flapping angles, rotation angles, and instantaneous lift force versus time during the asynchronous flapping oscillations at the resonant frequency of 70 Hz \(2d_0 = 4 \text{ mm} \text{ and } V_{\text{DC}} = 4 \text{ kV}\). g) and h), Measured flapping frequency and average lift force with respect to the gap distance between the two electrodes (under a fixed \(V_{\text{DC}} = 4 \text{ kV}\) and the applied DC voltage (under a fixed \(2d_0 = 4 \text{ mm}\), respectively.
Supporting Information). The high-voltage and small-current conditions, which can also be seen in the natural world such as sparks created by removing a nylon shirt or discharges generated by electric eels, allows the prototype to be easily powered by many kinds of existing technologies, such as ceramic capacitors, supercapacitors,\(^8,5^2\) and power generators in series.\(^5^3,5^4\) In this work, we choose ceramic capacitors as the power source for self-powered operations. Figure 5c shows the top view of the prototype in motion, where the angle, \(\alpha\), is defined as the flapping angle; \(\alpha\) is defined as the rotation angle; and \(L\) is defined as the distance between the two fulcrum bars (supporting points). Under a driving DC voltage, the wings can flap with twisting as shown in Figure 5d captured by a high-speed camera (CL600X2 from Optronis). Figure 5e shows the patterns of a natural flying bee.\(^5^5\) In these images, the blue solid lines represent the wing chord—the imaginary straight line joining the wing’s leading and trailing edges and perpendicular to the leading edge; and the red arrows in Figure 5a show the lift force generated by the wings which can be measured by a micro force sensor from Aurora Scientific Inc. with a resolution of 0.1 \(\mu\)N. It is found that the wing chord will change displacement as well as the inclination angle during the operation, which means that the wing’s rotational motion about the \(y\)-axis is induced during its flapping motion along the \(x\)-axis to increase the lift force on the downstroke and reduce the air drag on the upstroke.\(^1\) This self-adjustable rotating wing design has been proven to be a key factor to generate high lift force in natural flying insects.\(^5^5,5^6\)

Both wing motion (see details in Figure S5a, Supporting Information) and lift force (Figure S5b, Supporting Information) measurements have been conducted for the ground testing prototype #1a with adjustable electrodes. The continuous DC supply is utilized in these tests to avoid the variations in measurements from the pulse voltage inputs. Figure 5f shows the recorded flapping angle, \(\theta\), rotation angle, \(\alpha\), and instantaneous lift force, \(F_{l}\), with respect to time, \(t\) (Table S2, Movie 4, Supporting Information). It is observed that the flapping angle, \(\theta\), has a sinusoidal pattern with a frequency of 70 Hz and peak-to-peak angle variation of 39º. The rotational angle, \(\alpha\), follows the flapping angle pattern and can reach \(-38^\circ\) when the flapping angle reaches 19º. The phase difference between the flapping and rotational motion is a key factor for lift force generation.\(^5^5\) It is noted that the result is different with the self-adaptive experiment as the latter is not constrained and induced by the elliptical hole, and the wing length in prototype #1a is 12 mm which causes greater air damping force. The instantaneous lift force, \(F_{l}\), also has the sinusoidal pattern with an average value of 82 \(\mu\)N. The local maximum (minimum) of the lift force occurs with a value of 323 \(\pm\) 15 \(\mu\)N (–150 \(\pm\) 25 \(\mu\)N) when the flapping angle is around 0º. The zero lift force occurs when the flapping angle is at maximum (minimum) values. It should be noted that the rotational motion of the wing in the tested prototype does not work very well with the flapping motion due to the fulcrum bar structure with elliptical holes, and there is a period of time (e.g., 9–14 ms in Table S2, Supporting Information) when the angle of attack, \(\alpha'\), of the wings exceeds 90º to produce negative lift. The \(\alpha'\) is the angle between the wing chord and relative incoming velocity.

Figure 5g,h shows the frequency, \(f\), and average lift force, \(F_{LA}\), under different electrode gap distances (\(2d_0\)), and applied DC voltages (\(V_{DC}\)). It is observed that the frequency and lift force highly depend on the \(2d_0\) (structural parameter) and \(V_{DC}\) (corresponding to electrostatic force). A large gap distance is beneficial to generate an average lift force up to about 100 \(\mu\)N with \(2d_0 = 4.5\) mm in these tests with slightly lower flapping frequency at 59 Hz under a fixed \(V_{DC} = 4\) kV. For a prototype with a fixed electrode distance of 4 mm, a higher DC voltage (between 3 and 4.5 kV) results in a higher flapping frequency (from 62.5 to 76.0 Hz) and the maximum average lift force occurs at 88 \(\mu\)N when \(V_{DC} = 3.75\) kV. It is noted that the actual flapping frequency (62.5–76 Hz) is higher than the natural resonance frequency of the metal beams (48.2 Hz, calculated based on the bending stiffness of the beams) as the high driving voltage induces the spring stiffening effect of the beams.\(^5^7\)

2.5. Dynamic Modeling for Size and Efficiency Evaluations

For ground testing prototype #1a, the measured maximum average lift force generated by the flight muscle is 100 \(\mu\)N (corresponding to 10.2 mg). In other words, the force is not enough to lift an artificial flying robot, so further enhancements in the lift force-to-weight ratio are required. Similar to the natural flying insects, the artificial flight assembly can generate both the flapping and rotational motions, and the coupling effect between them should be considered. By using a simplified model of a lumped mass system with two degrees of freedom (DOF), both equations of flapping and rotation are derived based on the balance of forces (Figure S6a, Supporting Information), as shown in Equation (1).\(^3^9,4^9\) For the flapping motion equation, forces acting on the assembly include the electrostatic force \(F_E\); mechanical restoring force \(F_M\); aerodynamic damping force \(F_D\); and aerodynamic bending moment induced by the wing (\(M_A\)), where \(\lambda\) is the equivalent coefficient when the aerodynamic bending moment is simplified as aerodynamic damping force along the \(x\)-axis. For the rotational motion, the mechanical restoring torque \(T_M\) and the aerodynamic damping torque induced by the wing (\(T_A\)) are considered and the coupling terms (\(M_A, T_A\)) in the two equations imply that the flapping and rotational motions will affect each other.

\[
\begin{align*}
    m\ddot{x} + F_M(x) + F_D(x) + \lambda M_A(x, \dot{x}) &= F_E \\
    \dot{\alpha} + T_M(\alpha) &= T_A(x, \dot{x})
\end{align*}
\]

During the self-resonance, the flight assembly can hit the two stationary electrodes alternatively as analyzed in two stages: 1) during the impact, and 2) after the impact. In these two stages, forces acting on the beams have sudden changes due to the impact and they can be described by piecewise functions in Equation (2)-(4).\(^3^9\) whereas forces on the wings can be described in Equation (5)-(7) (see details in Table S5, Supporting Information).

The electrostatic force \(F_E\) can be calculated by Equation (2), where \(x\) is the displacement of the mass from its rest position; \(E_0\) is the electric field intensity between the electrodes; \(Q\) is the beam’s total charge when it hits one of the electrodes (negative or positive);\(^5^8\) and \(d_0\) is the gap distance between the beam and electrode.
The mechanical restoring force \( F_M \) can be derived in Equation (3), where \( k_1 \) and \( k_2 \)[9] are equivalent bending stiffness of the beams after impact and during impact, respectively.

\[
F_M = \begin{cases} 
  k_1 x, & -d_0 < x < 0 \\
  k_2 \frac{|x|}{d_0} (x - d_0), & x \geq d_0 \text{ or } x \leq -d_0
\end{cases}
\]  

The aerodynamic damping force \( F_D \) can be expressed in Equation (4), where \( c_1 \) and \( c_2 \)[9,7,9] are the equivalent damping coefficients of the beams after impact and during impact, respectively.

\[
F_D = \begin{cases} 
  c_1 x, & -d_0 < x < 0 \\
  (c_1 + c_2) x, & x \geq d_0 \text{ or } x \leq -d_0
\end{cases}
\]  

The aerodynamic bending moment \( M_A \), aerodynamic torque \( T_A \), and mechanical restoring torque \( T_M \) can be calculated by Equation (5)-(7)[9], where \( \rho \) is the density of air; \( A_w \) is the wing area; \( c_m \) is maximum wing chord width; and \( \overline{\tau}, \overline{\tau} \) are normalized coordinate values for the center of pressure shown in Figure S6b, Supporting Information; \( u_{CP} \) is the velocity of the wing at the center of pressure; \( C_N \) and \( C_t \) are flapping force coefficients; \( C_{rot} \) is the rotational force coefficient; and \( k_l \) is the equivalent torsional stiffness of the beams.

\[
M_A(x, \alpha) = \frac{\tau(L_d + L_w) \rho A_w u_{CP}}{2} \left[ (C_N u_{CP} + C_{rot} c_m \alpha) \cos \alpha - C_T u_{CP} \sin \alpha \right]
\]  

\[
T_A = \frac{\tau c_m u_{CP}}{2(C_N u_{CP} + C_{rot} c_m \alpha)}
\]  

\[
T_M = k_l \alpha \]  

As these equations are coupled differential equations for a nonlinear vibration problem with large amplitudes and dynamic impact processes, it is difficult to solve them analytically[9] such that the numerical Runge–Kutta method is utilized in this investigation. By solving the coupled equations (Equation (1)), we can obtain the variable \( x(t) \). The frequency \( f \) and flapping angle amplitude \( \theta_0 \) can be calculated by Equation (8).

\[
\theta(t) = \arcsin \left( \frac{x(t)}{0.5L} \right) \approx \theta_0 \sin(2\pi f t)
\]  

The useful aerodynamic power \( P_{out} \) is simply the sum of \( P_{drag} \) and \( P_{lift} \) (Equation (9)).[61] which are the average power dissipated for the aerodynamic drag and lift, respectively. The \( P_{drag} \) term can be estimated by quasisteady blade element analysis, as shown in Equation (10).[27,28,61–64] and the \( P_{lift} \) term can be calculated using the vortex theory of flapping flight, as shown in Equation (11).[61–63,65,66] Both \( C_{pro} \) and \( C_{ind} \) in Equation (10) and (11) are morphological coefficients of the wings[67,68] which are calculated by two different approaches in this work to verify the accuracy (see Table S7, Supporting Information, for details).

\[
P_{out} = P_{drag} + P_{lift}
\]  

\[
P_{drag} = C_{pro} (2\theta_0)^3 \int_{0}^{2\pi} \left( \frac{8}{3} \right) B_0 (2\pi \theta_0)^3
\]  

\[
P_{lift} = C_{ind} (2\theta_0)^{-4} \int_{0}^{2\pi} \left( \frac{F_{LA}}{4\rho \theta_0 (L_d + L_w)} \right)^2
\]  

\[
B_0 = \frac{1}{2} \rho C_D \int_{0}^{2\theta_0} r^3 c(r)dr
\]  

Power density \( (P_d) \) and efficiency \( (\eta) \) are the two most important evaluation criteria for small flying robots[69] and they can be estimated by Equation (13) and (14), respectively, where \( M_i \) is the mass of the flight assembly in this work. The average input power \( (P_{in}) \) in Equation (14) can be obtained by measuring the instantaneous current \( i(t) \) in the circuit as shown in Equation (15), where \( R \) is the resistance of the electrometer, \( T \) is the test time. In this work, \( i(t) \) is measured by a high-precision electrometer (6514 from Keithley) and processed by a fast data acquisition system (from National Instruments Corp.) (see Figure S5c, Supporting Information). Based on Equation (13)-(15), the efficiency of different prototypes in this work can be evaluated through experiments, as shown in Figure 6a and Table S6, Supporting Information. It is noted that lower applied voltage is used in Table S6, Supporting Information, for lower impact losses and higher efficiency, whereas the generated lift force is also reduced.

\[
P_d = \frac{P_{out}}{M_i}
\]  

\[
\eta = \frac{P_{out}}{P_{in}}
\]  

\[
P_{in} = \frac{1}{T} \int_{0}^{T} (V_{DC}(t) - i(t)^2 R)dt
\]  

Figure 6a shows the normalized maximum values of the flapping angle \( (\theta) \), rotation angle \( (\alpha) \), average lift force \( (F_{LA}) \), and frequency \( (f) \) with respect to the applied \( V_{DC} \) in both experimental (four data points) and simulation results with a starting voltage \( V_0 = 3 \text{ kV} \). As expected, increasing \( V_{DC} \) by 25% will result in increases in the rotation angle, frequency, flapping angle, and about 60% of higher lift force. Figure 6b shows the frequency \( (f) \) and power density \( (P_d) \) with respect to the single wing length \( (L_w) \) using measured (symbols) and simulation (lines) results from three fabricated ground testing prototypes with different sizes: prototype #1a: \( L_{w1} = 12 \text{ mm}, f_1 = 74 \text{ Hz}, P_{out} = 21.6 \text{ W kg}^{-1} \); prototype #1b: \( L_{w2} = 7.8 \text{ mm}, f_2 = 110 \text{ Hz}, \)
$P_{d2} = 28.8 \text{ W kg}^{-1}$; prototype #1c: $L_W = 5.0 \text{ mm}$, $f_3 = 170 \text{ Hz}$, $P_{d3} = 35.5 \text{ W kg}^{-1}$) as reference points (symbols in the figure). Figure 6b also shows that further miniaturization from the bee size ($L_W = 9.0–11.5 \text{ mm}$)\cite{70,71} to mosquito size ($L_W = 1.5–3.5 \text{ mm}$)\cite{72,73} based on the presented design and operation principle could lead to higher power density and frequency systems for possible fully autonomous artificial flights.

It is noted that the proposed artificial asynchronous mechanism via electrostatic actuation is in favor of miniaturization as compared with the existing synchronous mechanism via either electromagnetic or piezoelectric actuation. In principle, the scaling effect of the electrostatic force is proportional to the $L^0$, whereas the scaling effect of either electromagnetic or piezoelectric force is proportional to $L^2$.\cite{74} In other words, the electrostatic force is in favor of miniaturization\cite{75} as the scale ($L$) reduces, whereas both electromagnetic and piezoelectric actuation would result in faster reductions in the output force upon miniaturizations. We summarize both input power and efficiency versus the mass of various known flying systems in the designed operating states in Figure 6c,d (detailed analyses with calculations in Table S8, Supporting Information), to provide quantitative comparisons between the state-of-art artificial flying robots (blue color symbols and lines), natural flying insects (gray color symbols and lines), and this work (red symbols). Here, efficiency is defined as the ratio of the mechanical output power (equivalent to the aerodynamic power\cite{61}) to the electric input power for only the actuator part (flight muscle) of artificial flying robots. For real insect muscles, 40% of the chemical energy (stored in molecules such as glucose, fatty acids, and amino acids) is converted to bioenergy in the forms of ATP, and 25–50% of the bioenergy is converted to mechanical energy.\cite{76} As such, the overall efficiency from chemical energy to mechanical energy including the two stages is 10–20%. For the artificial flapping wings of this work, the electric energy is already stored in the capacitors to directly power the flapping wings with high efficiency. As expected, the required input power (Figure 6c) to actuate the artificial robots or natural insects reduces as their physical size reduces. However, the power reduction trend is slower for the robots (without the contributions of this work). In contrast, the efficiency (Figure 6d) of the robots reduces rather quickly as their size reduces from 19 g to 80 mg, whereas the efficiency of the insects remains at the same level as their size reduces to 0.6 mg. This work reverses these trends as illustrated—smaller input power was able to power the flying robots with high efficiency using the electrostatic asynchronous driving mechanism as a potential future direction for miniaturized flying robots.
For further demonstration, as shown in Figure 6c,d, DC motor-powered robots heavier than 10 g$^{[77–79]}$ have high input power and efficiency of more than 2 W and 70%, respectively; As the body mass reduces to below 10 g, the power and efficiency reduce to 0.46 W and 46%,$^{[27,28,80,81]}$ For miniaturized flying robots with mass in the range of 80–300 mg driven by piezoelectric and electromagnetic means, the power consumptions are generally less than 1.2 W with efficiencies less than 10%.$^{[1,23,25,82,83]}$ In contrast, the power consumptions for natural flying insects also gradually decrease with respect to mass, whereas their efficiencies are in the range of 10–20% even if the mass decreases to below 1 mg.$^{[31,61,63,84–87]}$ This work shows the ground testing prototypes driving by electrostatic actuation can have masses in the range of 2.9–25.4 mg with measured input power of 0.0286–0.323 mW resulting high efficiencies in the range of 36.0–38.5%. As a result, the remarkably low power consumption makes our devices have the potential to be powered onboard by solar cells,$^{[89]}$ in favor of miniaturizations for future flying insects with untethered, long-endurance, and autonomous flights.

### 3. Discussion

The asynchronous driving mechanism and the electrostatic actuation$^{[75,89]}$ result in remarkably simple artificial flight muscle structures without complex power electronics (such as boost circuits), whereas further miniaturizations can lead to better operating frequency with good efficiency and lift force-to-input power ratios. Specifically, detailed comparisons with other similar-sized alternatives have been made based on model equations used in this work, as shown in Table S8, Supporting Information. Compared with most other similar-sized alternatives, our testing prototypes have smaller weights, similar operation frequency, higher efficiencies for the lift force-to-input power ratios, and self-adaptive characteristics in terms of both flapping frequency and flapping amplitude when a disturbance is introduced. However, the output power density (output power divided by the mass of the flight muscle) is generally lower than those of other works using piezoelectric/electromagnetic actuation or real insects, as shown in Table S8, Supporting Information, whereas the electrostatic driving mechanism used in this work is in favor of further miniaturizations. As such, these comparisons and analyses imply possible optimizations at the current scale for further improvements and overall system miniaturizations in the future to fully take the advantage of the electrostatic driving mechanism for better performances.

There are two main limiting factors for the asynchronous flight muscle to lift artificial flying robots. 1) The electrostatic driving force is not large and efficient enough at the current size range but could become greater with further miniaturization.$^{[74]}$ 2) The airframe may occupy much of the whole body mass, which is too heavy to be lifted. For example, the similar-sized alternatives have airframes that only occupy about 6.25–13.75% of the whole weight as shown in Table S4, Supporting Information. In other words, our future works will need to reduce the airframe portion of the prototypes to increase the power density (over the whole weight of the prototypes). For example, ultralight weight materials with precision manufacturing technologies could be used to drastically reduce the airframe mass, and further miniaturizations to the microelectromechanical systems (MEMS) scale electrostatic actuators, such as the comb drive structures$^{[81]}$ could increase the efficiency of the electrostatic driving force based on the scaling analyses.$^{[74]}$ Our model has predicted that further miniaturizations of the size of testing prototypes can result in a larger power density. Specifically, the scaling effect of the electrostatic force is proportional to the $L^3$, whereas the scaling effects of the inertial, elastic, and viscosity forces are proportional to $L^2$, $L^2$, and $L^2$,$^{[74]}$ respectively. In other words, as the scale ($L$) reduces, the electrostatic force will outgain other electromagnetic/piezoelectric force for higher power density.

In the current prototypes, the voltage requirements are several kV and it is challenging for the onboard power sources. As described earlier, miniaturization is one path to increase the efficiency of the prototypes using electrostatic force, while miniaturization also reduces the voltage required to power the prototypes. For example, as the wingspan decreases from 4.9 to 2.0 cm in our prototype demonstrations, the minimum operating DC voltage reduces from 2.4 to 1.0 kV (Table S6, Supporting Information). Our previous works have also shown that the operating DC voltage of the self-sustained electrostatic actuator could be reduced by miniaturizations.$^{[89]}$ In contrast, the current consumptions of our flight muscle (using DC voltage) are very low as compared with those of similar-sized alternatives (using AC voltages and large operating currents). This high-voltage and small-current operating conditions are common in the natural world such as sparks created by humans taking off a nylon shirt or discharges generated by electric eels. Furthermore, our devices can already be powered by existing technologies, such as ceramic capacitors, supercapacitors,$^{[85,82]}$ and power generators connected in series.$^{[53,54,89]}$ For onboard high-voltage power generation, solar cells can be potentially connected in series to generate high DC voltages.$^{[89]}$

### 4. Conclusion

In this work, the operation of natural asynchronous flight muscles in flying insects has served as the inspiration for the driving mechanism of the asynchronous flight assembly based on self-sustained electrostatic oscillations. There is a direct analogy between this approach and biological mechanisms, in which electrons (in the artificial system) play the role of calcium ions (in the biological structure) to regulate and maintain the asynchronous motions. Both guided takeoffs along the U-shaped rail electrodes and the self-adaptive hovering of the flight assembly via the passive modulation of the flapping frequency and amplitude have been demonstrated. The simple operating principle based on electrostatic actuation allows the usages of a variety of conductive materials (super-elastic SMA and so on) without AC circuits. As such, ground testing prototypes in the milligram range (2.9–25.4 mg) have been constructed to achieve high energy efficiencies (36.0–38.5%). Based on the dynamic model for the asynchronous driving mechanism with simulation results coupled with several experimental data, it is observed that both the frequency and power density of our devices can be furthered improved by decreasing the total size (weight) to subcentimeter.
(submilligram) ranges. Using other precision manufacturing technologies, such as MEMS or precision machining, further miniaturized flying robots powered by artificial flight muscles could be constructed with the improved lift force-to-weight ratio for untethered autonomous flights based on the asynchronous flight mechanism.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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artificial muscles, asynchronous mechanism, biologically inspired robots, biomimetics

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