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Designing a Biomimetic Ornithopter Capable of Sustained and Controlled Flight

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Abstract

We describe the design of four ornithopters ranging in wing span from 10 cm to 40 cm, and in weight from 5 g to 45 g. The controllability and power supply are two major considerations, so we compare the efficiency and characteristics between different types of subsystems such as gearbox and tail shape. Our current ornithopter is radio-controlled with inbuilt visual sensing and capable of takeoff and landing. We also concentrate on its wing efficiency based on design inspired by a real insect wing and consider that aspects of insect flight such as delayed stall and wake capture are essential at such small size. Most importantly, the advance ratio, controlled either by enlarging the wing beat amplitude or raising the wing beat frequency, is the most significant factor in an ornithopter which mimics an insect.

Keywords: biomimetic, ornithopter, flapping wing, unsteady state, low Reynolds number

1 Introduction

Flapping flight, especially insect flight, has fascinated humans for many centuries, since its flapping technique remains unsurpassed in many aspects of aerodynamic performance and maneuverability. We have been studying flapping Micro Aerial Vehicle system (MAVs) since 2004 and have succeeded in flying a 15 cm span ornithopter composed of electric pager motor weighing less than 10 g at the MAV07 Conference held in France September 2007.

A biomimetic flapping vehicle should follow the flight principles of insect wing (shown in Fig. 1) and should have a complicated flapping mechanisms in order to be more able and maneuverable, such as taking-off backwards, flying sideways, and landing upside-down[1] as insects do. However, there are many difficulties in building an efficient flapping mechanism as well as fabricating biomimetic wings due to limited materials and actuators. Recently, there has been tremendous progress in the observation of insect's flapping flight, and it is possible to adopt its design for an MAV that can fly by flapping[2] and in sustained flight.

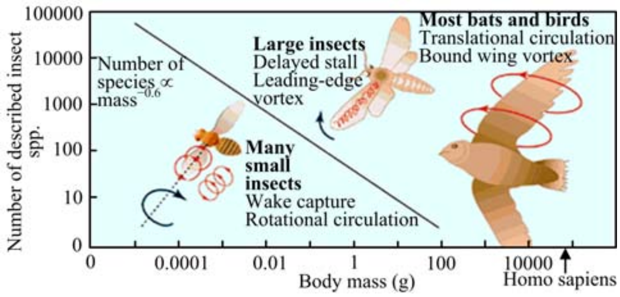

Fig. 1 Flight mechanisms of natural flyers.

By designing, fabricating and testing each subsystem as well as the wing structures of different ornithopters, we have optimized the most efficient flapping MAV system. First, we expected to maximize the abilities in both maneuverability and practical applications, such as an independent mission executed by an auto-control system. Second we expected to achieve the same size as an insect by imitating the flight mechanisms and actuating structures of insects. In this work, we attempted to analyze and characterize our four different size ornithopters so as to get a clear vision and analysis of an ornithopter which could lead us to the next step in developing a more sustained and controlled ornithopter

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which can hover.

2 Characteristics of low Reynolds number aerodynamics applied to flapping MAV

At low Reynolds numbers, especially in flapping flight, there are many remarkable results that prove the advantages of unsteady aerodynamics. At the size of insects, lapping wings benefit from unsteady aerodynamics more than steady-state aerodynamics to generate lift, as well as have high maneuverability and agility as seen in insects and hummingbirds. Biological flight systems, known as the most efficient flight mechanism, are also superior to engineering flight systems at all small scales for their better power supply, better stability and control system, flying in fluctuating conditions and at low Reynolds numbers.

Small insects have a wing chord Reynolds number between 100 and 1000, use unsteady effects to stay aloft and have corrugated, curved plates for wings. In the range from large insects to small birds, the wing chord Reynolds number lies between 1000 and 15000 and they use conventional airfoil circulation and are sensitive to transition and separation.

As the size of MAV decreases with higher wing beat frequency, features of the unsteady flight regime become more critical. In order to fulfill those characteristics, we focused on analyzing flight mechanisms and wing structures of insects and adapted those characteristics for our flapping vehicle. Moreover, we intended to improve our flapping vehicles by comparing the flight mechanism of insects and tried to find the differences in order to specify the requirements for improving the vehicle's performance, the final purpose of our research.

As shown in Fig. 2, flight mechanisms and aerodynamic characteristics vary over different Reynolds number regimes. From Pennycuick[3] the relation between flight speed and the mass of a bird can be given by

$$U = 4.77m^{1/6}, \tag{1}$$

where U is the flight speed in m·s^{-1} and m is the mass in g. Greenewalt[4] computed from statistical data the correlation between wing flapping frequency f (Hz), vs. wing length l (cm), to be

Most small insects $100<Re<1000$	Large insects to small birds $1000<Re<15000$	Birds $15000<Re$
		
-Delayed stall -Wake capture -Rotational circulation	-Dynamic stall -Delayed stall -Wake capture	-Bound circulation -Quasi-Steady mechanisms

Fig. 2 Comparison of flight characteristics over different Reynolds number.

$$fl^{1.16} = 3.54 . \tag{2}$$

While Azuma[5] showed that the correlations between wing flapping frequency f (Hz) and mass, m (g), for large birds and small insects are

$$f\,(\text{large birds}) = 116.3m^{-1/6}, \tag{3}$$

$$f\,(\text{small insects}) = 28.7m^{-1/3}. \tag{4}$$

From Eqs. (1)–(4), relationships between wingtip speed and mass can be derived. These relations are

$$\text{Wingtip speed (large birds)} = 11.7m^{-0.065}, \tag{5}$$

$$\text{Wingtip speed (small insects)} = 9.7m^{-0.043}. \tag{6}$$

For larger flyers, flight can be approximated by quasi-steady state assumptions because their wings flap at low frequency during cruising. Hence the wingtip speed is lower compared to the flight speed. So larger birds, such as eagles and seagulls, tend to have soaring flight and their wings behave like fixed wings. On the other hand, smaller birds and insects fly in an unsteady state, e.g., flies and mosquitoes flap their wings at several hundred Hz. From the results of other researches and papers[6], we assume that our flapping MAVs would operate in an unsteady state flow regime in which the wingtip speed is faster than the flight speed and fluid motion is complicated and not constant over time.

The reference attached in Fig. 3 shows the aerodynamic performance of natural insect wings, carbon fiber wings, and MEMS wings. It shows that spanwise stiffness is an important factor in lift production in flapping flight[7]. For the same size of wings, cicada wings with a rigid leading edge produce larger lift coefficients.

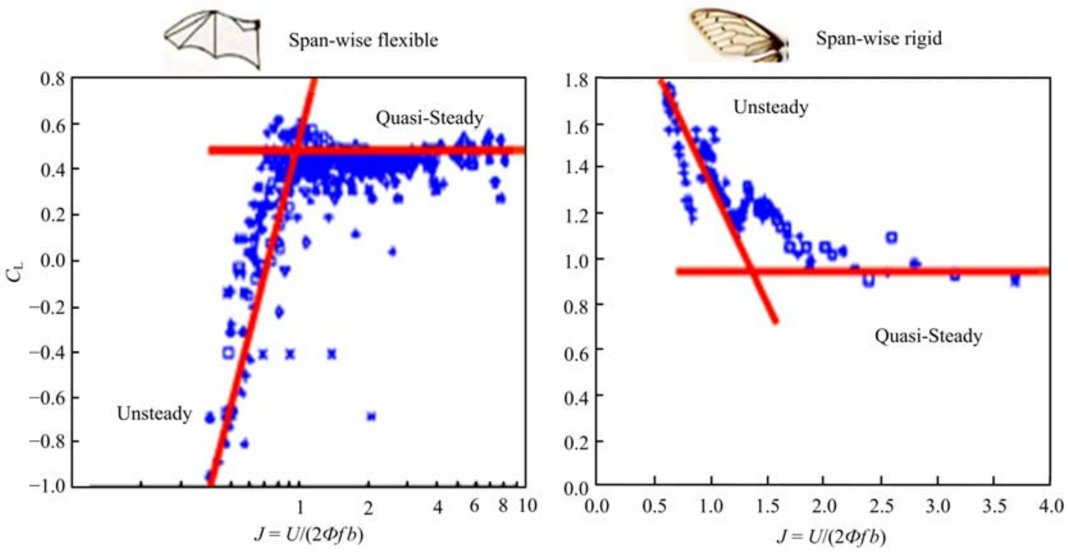

Fig. 3 Stiffness distribution effects on lift performance.

Because the lift coefficient of the rigid spanwise is higher than that of the flexible spanwise in unsteady state flight, we used carbon fibre to make the span structure of a mechanical ornithopter which is sufficiently rigid. The ornithopter mechanism is designed such that the wings move up and down and produce flapping along the wing chord due to the wing's elasticity. That means the structural elasticity along the chord direction is an important factor. The wing frame is an important part controlling the elasticity of whole wing and thus the structure of the wing frame affects the efficiency and deformability of the wing.

3 Wing design and fabrication

3.1 Analysis of the cicada wing

No insect flies only by flapping. They fly through complex flight mechanisms such as delayed stall, rotational circulation, and wake capture. But there is no flapping mechanism which can perform those actions at the same time, so we recommended making wings which mimic the wings of insects and improve flight efficiency through applying those wings to our vehicle.

We made several wing models which mimic insect wings and evaluated their efficiency. After analyzing the wings of cicada, we found that a cambered wing is divided into many cell-type membranes formed with veins throughout the whole wing area[8]. The leading edge vein is thicker than the other veins and the thickness reduces from wing root to wing tip. This shows that the insect wing is an efficient structure for unsteady flight by having differences in the thickness of the veins and the size of cells surrounded by those veins. With camber in both spanwise and chord directions, it can control wing deformation during flapping.

3.2 Cell-type wing

Keeping the features of the wing in Fig. 4 in mind, we tried adding more frames with cell-type wing (shown in Fig. 5) design instead of the two frames design and adopting camber in the spanwise direction design. We used carbon fiber to form the main spar and each sub frame. To stiffen the wing along the span, we made the main spar thicker.

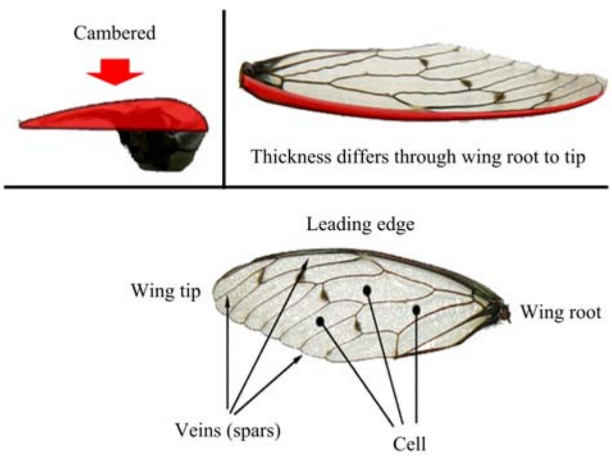

Fig. 4 Characteristics of insect wing (cicada).

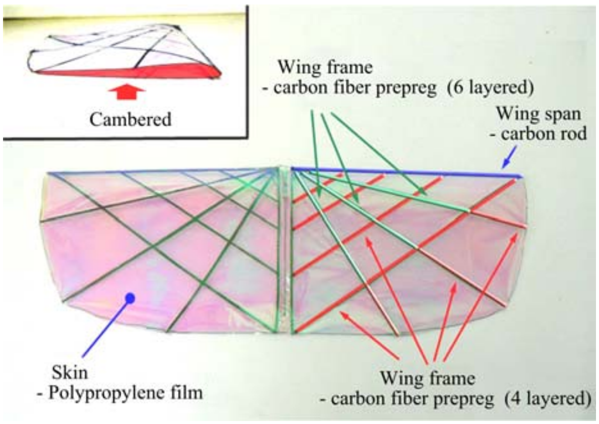

Fig. 5 Cell-type wing made up with composite material.

3.3 Cambered wing

A thin airfoil was used to minimize drag, suitable for low Reynolds number. By using X-foil software, the EH3012 airfoil was cut from the leading edge by 7.7% and only the airfoil with the upper surface was designed (Fig. 6).

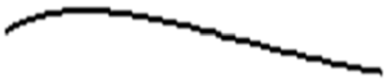

Fig. 6 Airfoil EH3012.

3.4 Fabricating

We made a mold to fabricate the cambered and cell-type wing. The procedure of fabrication is shown in Fig. 7.

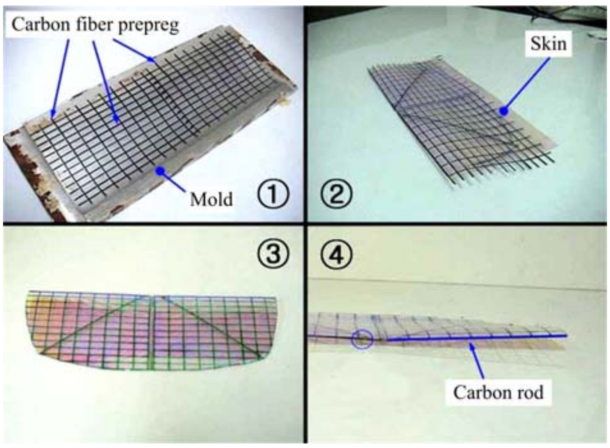

Fig. 7 Procedures of bio-mimetic wing fabrication.

4 Transmission design

4.1 Power system design

In order to calculate the necessary power, based on the approximate weight, wing span and flying speed, we investigated several motors. We selected a light weight commercial motor, B2C, manufactured by the GWS Company. Fig. 8 shows the expected motor performance. We chose an appropriate gear reduction ratio.

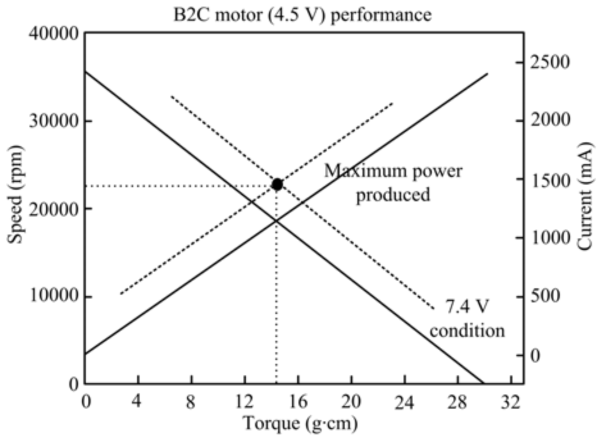

Fig. 8 Motor efficiency graph.

The B2C motor is powered by 4.5 V nominal. But the battery to be used gives 7.4 V and the voltage consumed at the motor would be 6.8 V. Thus the no load speed of the motor would be 35,550 rpm. and the maximum power would be produced at half this, 17,775 rpm. The torque loading on the wing would be approximately 300 g·cm. Therefore the appropriate gear reduction ratio is 28:1, and the available reduction ratio is 24:1 which also can produce necessary torque. The wing flapping frequency is then 12 Hz.

4.2 Gear box design

We designed three types of gear box connected to the crank shaft. We experimented with the advantages and disadvantages of these designs while assembling and testing each type.

According to the mechanism features (Fig. 9), type A transfers large force because two connecting cranks from the two final gears are connected to each wing spar which divide the total force delivered to the wing so that the crank could generate a higher force. It also produces less vibration due to the lower moment affected by the gear system due to the contrarotation. But they are relatively heavy. Type B is not very efficient because the flapping of the left and right wings could not be symmetrical which would reduce flight efficiency. But it is lighter than the other gear box designs and easier to repair. So we chose this design for the first ornithopter. Type C generates more vibration, but in flight tests it didn't really affect the flight performance significantly. Since it appears to be the most favorable in both weight and performance, we chose type C as the main gear box.

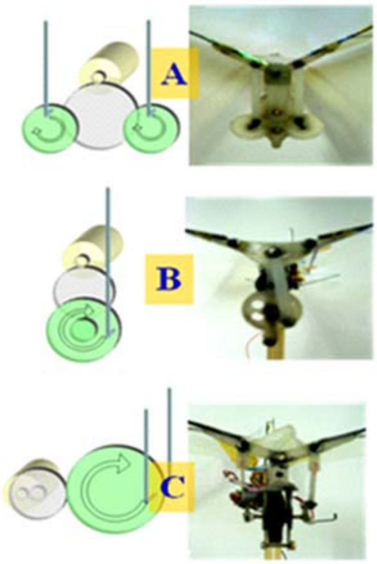

Fig. 9 Concept design of three types of gear box.

The gear box should be stiff and light, so we used glass plate as a material. We designed it using CATIA software and manufactured it with a CNC machine. We made the fuselage form the body but later we used only the gearbox and supporting frames so as to reduce the weight.

4.3 Tail design

We tested two types of tail, one with a stabilizer and one without. Design was motivated by conventional airplane tail design, much like a conventional fixed wing airplane. Because of the limit of current technology, it is not possible to implement a complicated combination of main wing and tail as in a bird to a mechanical ornithopter to control flight direction. Only by observation of the ornithopter's flight could we know the properties of each type, so we made several flight tests to find out the advantages and disadvantages of each type.

The tail with the stabilizer could keep straight and level flight and was very easy to control but it lacked maneuverability, in other words there was delay in turning and correction by rudder control. A vertical tail (Fig. 10) with no stabilizer was more maneuverable but significant negative pitching moments were observed when the rudder was at a large angle. To compensate the negative pitching moment in turning, a horizontal tail (Fig. 11) was installed at -18° to the wing. The horizontal stabilizer was also configured after flight testing to achieve the most efficient shape and placement.

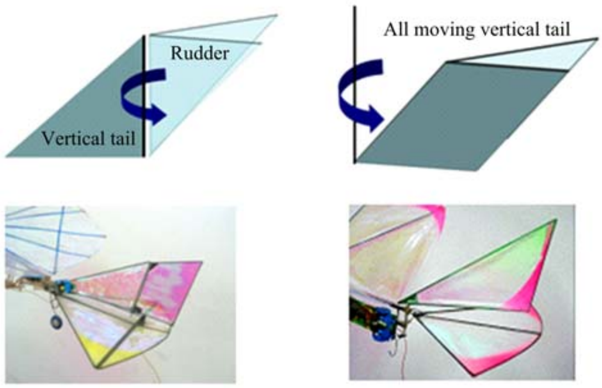

Fig. 10 Vertical tail design.

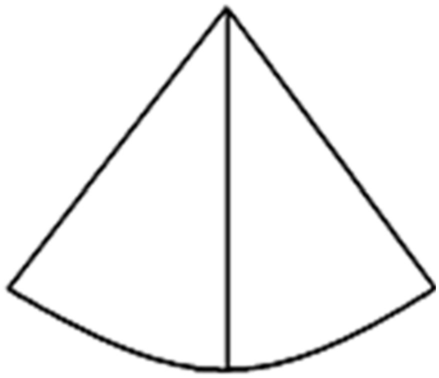

Fig. 11 Horizontal tail design.

5 Prototype vehicles with specification

5.1 36 cm ornithopter capable of takeoff and landing with vision sensor

(1) Vision transmission method: To provide out-of-sight guidance, we mounted a miniature video camera on the front of the vehicle with a transmitter in order to send images. As shown in Fig. 12, it was placed

to point at the ground 30˚ downward from the flight direction. If we can get a smaller and lighter vision system, we will use it with the smaller flapping MAV. Although some images received were fuzzy and vibrating due to the flapping motion, the images were good enough to control the vehicle by vision only. Problems with vibrating images and noise can be solved by image filtering in the ground system and the development of our own image modification software. The specification of 36 cm ornithopter is shown in Table 1.

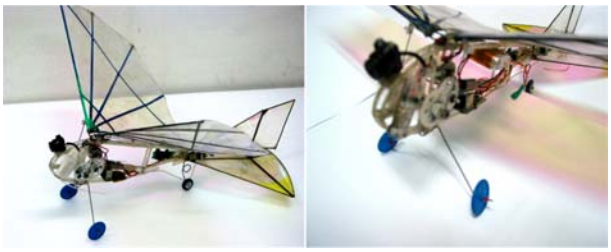

Fig. 12 36 cm ornithopter.

Table 1 Specification of 36 cm ornithopter

Component part	Mass (g)	Wing span	36 cm
Motor	6.09	Wing area	432 cm^2
Battery	10.2	Weight	50 g
Speed controller	1.22	Wing loading	0.115 $g \cdot cm^{-2}$
R/C receiver	2.04	Fuselage	25 cm
Fuselage and gear box	20.71	Gear ratio	28:1 reduction
Wing	4.35	Frequency	20 Hz
Camera &transmitter	+6.05	Up stroke	35˚
Total mass	44.60 (+6.05)	Down stroke	0˚
		Flight duration	15 min

(2) Takeoff and landing system design and configuration: we also implemented landing gear for takeoff and landing. The best design was like one used in a full-size aircraft, with three wheels attached to the fuselage at 22˚ from horizon. It could successfully manage to take off and land within 3 m which will improve its maneuverability and survivability under any kinds of mission.

5.2 28 cm ornithopter with high maneuverability

The 28 cm ornithopter (Fig. 13) was designed to execute a competitive mission in the International Air Vehicles Competition. The mission is to fly 8 or O shaped turns between two poles separated by 12 m as many times as possible in a given time. To accomplish this, it is necessary to make the body as small as possible, the flying speed as fast as possible and to be very controllable. Because it needs to have sharp and rapid turning, we focused on high maneuverability. It is designed to have higher speed and maneuverability so we chose an all moving rudder and elevator mechanism for fast reaction and a frameless fuselage for lightness. The specification of 28 cm ornithopter is shown in Table 2.

Fig. 13 28 cm ornithopter.

Table 2 Specification of 28 cm ornithopter

Component part	Mass (g)	Wing span	28 cm
Motor	6.09	Wing area	280 cm^2
Battery	7.94	Weight	30.6 g
Speed controller	1.22	Wing loading	0.109 $g \cdot cm^{-2}$
R/C receiver	2.04	Fuselage	23 cm
Fuselage and gear box	6.44	Gear ratio	19:1 reduction
Wing	3.27	Frequency	24 Hz
Total mass	30.60 (+3.05)	Up stroke	30˚
		Down stroke	5˚
		Flight duration	8 min

5.3 15 cm ornithopter capable of sustained flight

At the same time we were trying to make the world's smallest ornithopter, optimizing the ornithopter system and searching for the lightest components. There was no choice but to use the most compact and small components in order to reduce weight and size as much as possible. As shown in Fig. 14, it doesn't have an elevator but uses flapping frequency to maintain or change its altitude by controlling the speed of the motor. The force generated by a 15 cm wing was not sufficient to fly in a wind velocity of higher than 2 $m \cdot s^{-1}$, so most of the flight tests were held indoor. After succeeding in its first flight, detailed modification and optimization proceeded. Finally, we attained a field flight duration of 1 min. The specification of 15 cm ornithopter is shown in Table 3.

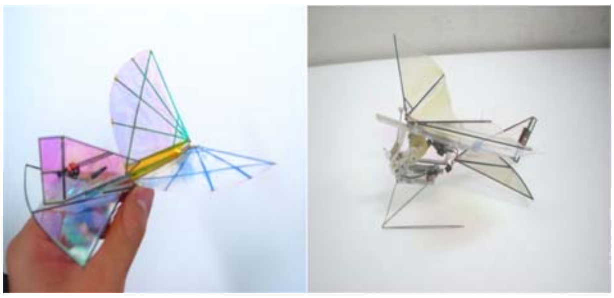

Fig. 14 15 cm ornithopter.

Table 3 Specification of 15 cm ornithopter

Component part	Mass (g)	Wing span	15 cm
Motor	1.6	Wing area	85 cm^2
Battery	1.3	Weight	8.7 g
Speed controller	0.8	Wing loading	0.102 $g\cdot cm^{-2}$
R/C receiver	0.8	Fuselage	12 cm
Fuselage and gear box	4.3	Gear ratio	16:1 reduction
Wing	0.8	Frequency	30 Hz
Total mass	8.7	Up stroke	40°
		Down stroke	5°
		Flight duration	1 min

5.4 10 cm ornithopter capable of controlled flight

Current technology could bring us to develop a smaller ornithopter, with 10 cm wing span with X-wing design (shown in Fig. 15). We have concluded that we need to innovate the design to make less than 10 cm ornithopter in order to have sufficient lift and thrust. This is why we chose the X-wing type of flapping ornithopter. The battery was another important consideration since it became the heaviest component of the whole system which limited us to use very low capacity battery. Although it has only 30 s flight duration, we expect to extend the duration by developing a more efficient and lighter propulsion system and a battery with greater capacity. The specification of 10 cm ornithopter is shown in Table 4.

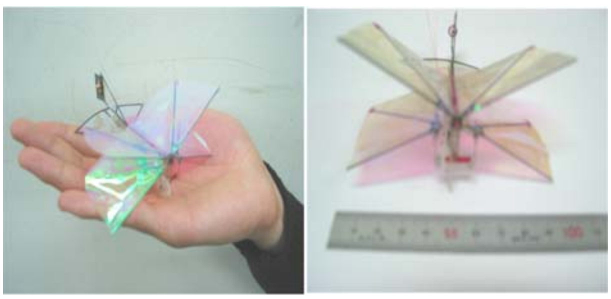

Fig. 15 10 cm ornithopter.

Table 4 Specification of 10 cm ornithopter

Component part	Mass (g)	Wing span	10 cm
Motor	0.67	Wing area	59.85 cm^2 119.7 cm^2
Battery	1.0	Weight	4.32 g
Speed controller	0.8	Wing loading	0.072 $g\cdot cm^{-2}$ 0.036 $g\cdot cm^{-2}$
R/C Receiver	0.8	Fuselage	7.5 cm
Fuselage and gear box	1.45	Gear ratio	14:1
Wing	0.8	Frequency	35
Total mass	4.72	Up stroke	30
		Down stroke	30
		Flight duration	< 30 s

6 Analysis on aerodynamic parameters and results

The lift and thrust coefficients can be expressed as

$$\begin{cases} C_{\mathrm{L}} = \dfrac{2L}{\rho A U^2} \\ C_{\mathrm{T}} = \dfrac{2T}{\rho A U^2} \end{cases}, \tag{7}$$

where L, T, U, A, ρ, are lift, thrust, flight speed, wing area, and air density, respectively. The advance ratio J is the ratio of the flight speed to the speed of the wingtip and is given by

$$J = \frac{U}{2\Phi fb}, \tag{8}$$

where Φ, f, b are stroke angle, flapping frequency, and wing semi-span, respectively. In order to estimate the flying speed, necessary to calculate the advance ratio J. We refer to Fig. 16 which shows the relation between flying speed and the weight of birds or insects, obtaining Eq. (9) as the result[9].

$$U = 4.77W^{1/6} \tag{9}$$

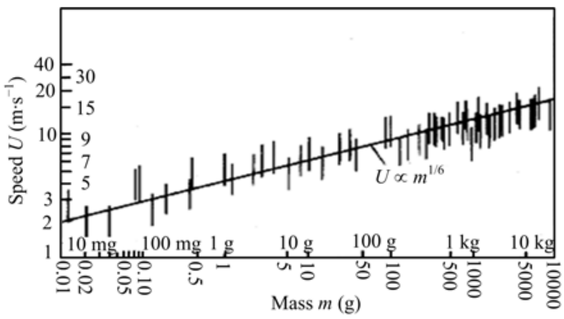

Fig. 16 Flight speed of birds and insects.

Because the current mechanical ornithopter is expected to be less efficient than natural flyers, the maximum speed of a mechanical ornithopter would be less than the speed calculated from Eq. (9). The measured speed of the 36 cm ornithopter was approximately 6.5 $m\cdot s^{-1}$, which was about 25% less than the calculated speed. We therefore assume that the actual flight speed is 25% slower than that of birds or insects. So speed calculated by Eq. (9) should be multiplied by a factor of 0.75. The parameters of the ornithopters are given in Table 5.

Table 5 Morphology, kinematics and advance ratio

Wing span (cm)	36	28	15	10
Morphology				
m (mg)	5000	3060	870	430
R (mm)	360	280	150	100
AR	3	2.7	2.5	2.4
Kinematics				
n (Hz)	20	24	30	35
F (deg)	35	35	45	60
F (rad)	0.097	0.097	0.125	0.166
$U = 0.75\times4.77W^{1/6}$	6.847	6.296	5.115	4.543
$J = U/2\Phi fb$	0.978	0.964	0.909	0.779

Typically, unsteady state flight has an advance ratio of less than 1. For example, natural fliers such as the bumblebee, blackfly, and fruit fly have advance ratios in free flight of 0.66, 0.50, and 0.33, respectively[10,11]. According to these references and comparison data of advance ratio versus wing length shown in Fig. 17, our ornithopter is confirmed to be in the unsteady state aerodynamic regime. Insects have a lower advance ratio relative to wing span which means that their wings move faster with higher wing beat amplitude.

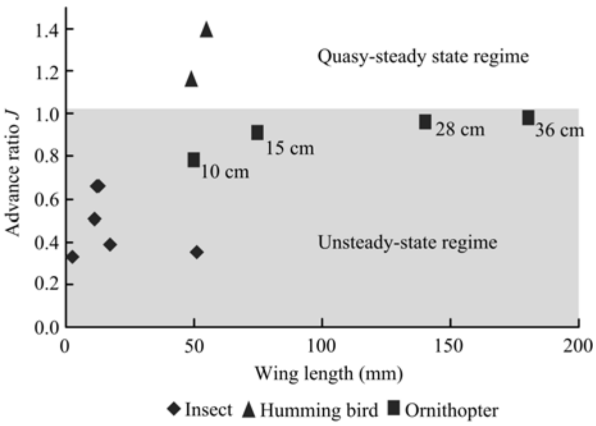

Fig. 17 Advance ratio vs wing length.

The aerodynamics of insect flight is affected by the scaling of the Reynolds number *Re*, which is the ratio of inertial to viscous forces in a fluid. *Re* is defined as the product of a characteristic length and velocity divided by the kinematic viscosity, *v*, of the fluid. For comparison, we can conveniently ignore the forward velocity and define a mean *Re* for hovering flight based on the mean chord $\bar{c} = 2R/AR$ and the mean wingtip velocity $\bar{U}_t = 2\Phi nR$ [12]:

$$Re = \frac{\bar{c}\bar{U}_t}{v} = \frac{4\Phi nR^2}{vAR}, \tag{10}$$

where *AR* is the aspect ratio, *n* is the wingbeat frequency, *R* is the wing length and Φ is the wingbeat amplitude (peak to peak, in radians). For large insects, *Re* lies between 5000 and 10,000, but it approaches 10 for the smallest ones. In all cases, the airflow is in the laminar regime, but viscous effects become progressively more important as size decreases[13]. Based on this report, we calculated the values of *Re* of our ornithopters as shown in Table 6, which lead us to conclude that our ornithopters are entering the small insect regime. This also shows that our flight efficiency as well as designs and mechanism steadily improve to follow that of nature. So far, we have reached the governing equation to develop our designed ornithopter in terms of the relationship between wing length and Reynolds number as shown in Fig. 18, which is given by

$$Re = 30.24R - 2.833. \tag{11}$$

Table 6 Reynolds number of ornithopter

Wingspan (cm)	36	28	15	10
Re	21,538.46	17,372.58	8653.84	6232.19

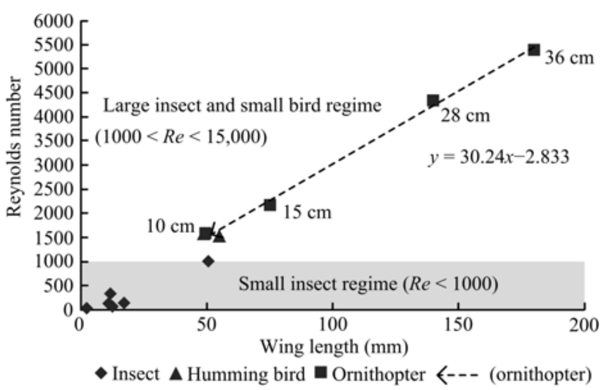

Fig. 18 Reynolds number vs wing length.

This is one of our meaningful achievements through this research because we can derive suitable wingbeat frequency and wingbeat amplitude through Eq. (11).

7 Conclusions

The first prototype of ornithopter was flown for less than 1 min in Dec, 2004. Its wingspan was about 40 cm and weighed around 45 g. We succeeded in reducing its size to 10 cm and its weight to less than 5 g. Although this 10 cm ornithopter can not fly in a wind velocity over 2 m·s^{-1}, it is very challenging and promises the possibility of making a mechanical flapping vehicle as small as an insect. We concluded that there are several challenges in order to achieve a successful sustained and controlled flight with smaller wings.

First, the flapping mechanism that could perform much like the insects, such as delayed stall, wake capture, rotational circulation, has to be developed in order to obtain advanced flapping techniques. Second, decreasing the advance ratio, by either enlarging the wing beat amplitude or raising wing beat frequency, is the most significant factor in an ornithopter which mimics an insect. Third, we have classified and defined the characteristics of four types of ornithopter through aerodynamic analysis and comparison with birds and insects and derived a relationship between Reynolds number and wingspan of our ornithopter. Finally, the best solution is to make an ornithopter under unsteady state flight regime, and we believe that an ornithopter smaller than 10 cm should follow the features of much smaller insects based on their wings and flight mechanisms. Thus we expect an ornithopter can be optimized and improved.

Acknowledgement

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