

Design and Development of Multi Ornithopter using Bio-mimic Method and Analysis

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Abstract

In this paper, the design for compactable ornithopter which is varied along the span from 10 cm to 40 cm, and weight of 5 to 45 Kg. The major considerations are controls and power supply because current ornithopter is radio-controlled with inbuilt visual sensing and capable of takeoff and landing. This proposal shows that wing efficiency based on design inspired by a real insect wing and considers that aspects of insect flight such as delayed stall and wake capture are essential at such small size. Not only have they compared the efficiency and characteristics between different types of subsystems such as gearbox and tail shape. 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.

The most critical part of the ornithopter is the drive mechanism that converts the electric power from the battery to the flapping motion of the wings. This system is the most complex to design and fabricate because it must withstand very large forces which reverse the direction several times a second while at the same time being extremely light and durable. Because of the loads it must be made from metal, which makes it beneficial to perform careful analysis and trim as much weight as possible.

Index Terms: Ornithopter, flight, capture, gearbox, significant, mimics, mechanism, flapping, fabricate, analysis.

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 15cm span ornithopter composed of electric pager motor weighing less than 10g at the MAV07 Conference held in France September 2007. A biomimetic flapping vehicle should follow the flight principles of insect wing (shown in Figure 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 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 and in sustained flight.

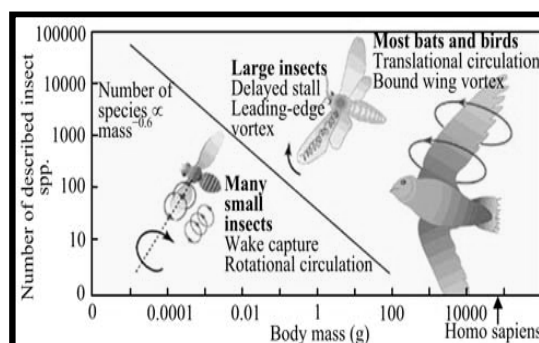


Fig. 1: Flight mechanisms of natural flyers.

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, flapping 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 humming birds. 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 relation between flight speed and the mass of a bird can be given by

$$U = 4.77m^{1/6}, \quad (1)$$

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

$$fl^{1.16} = 3.54. \quad (2)$$

While Azuma[5] showed that the correlations between wing flapping frequency f (Hz) and mass, m (g), for large birds and small insects are $f(\text{large birds}) = 116.3m^{-1/6}$, (3)

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

From Equations. (1)–(4), relationships between wingtip speed and mass can be derived. These relations are Wingtip speed (large birds) = $11.7m - 0.065$, (5)

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




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.

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 Figure 3 shows the aerodynamic performance of natural insect wings, carbon fiber wings, and MEMS wings. It shows that span wise 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.

Because the lift coefficient of the rigid span wise is higher than that of the flexible span wise in unsteady state flight, we used carbon fiber 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.

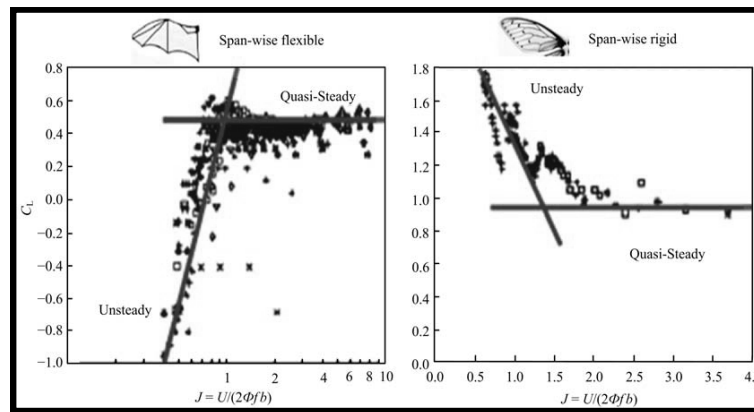


Fig. 3: Stiffness distribution effects on lift performance.

2. Wing design and fabrication

2.1 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 span wise and chord directions, it can control wing deformation during flapping.

2.2 Cell-type Wing

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

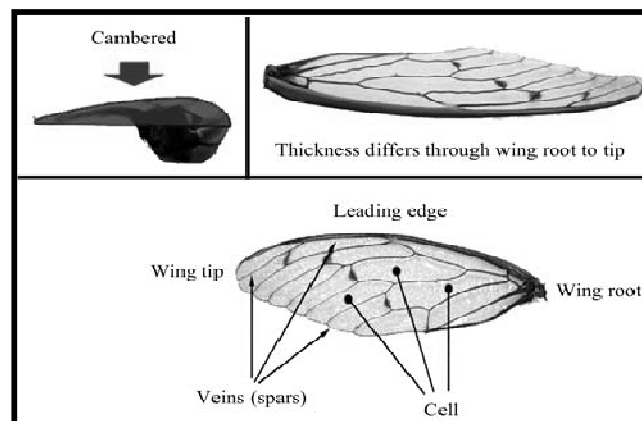


Fig. 4: Characteristics of insect wing (cicada).

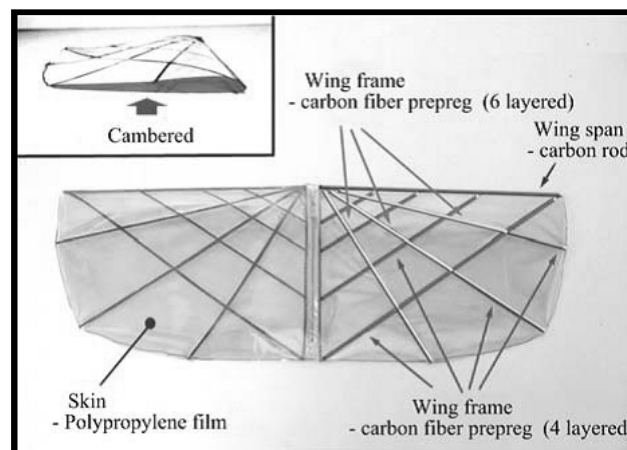
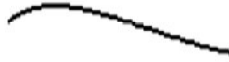
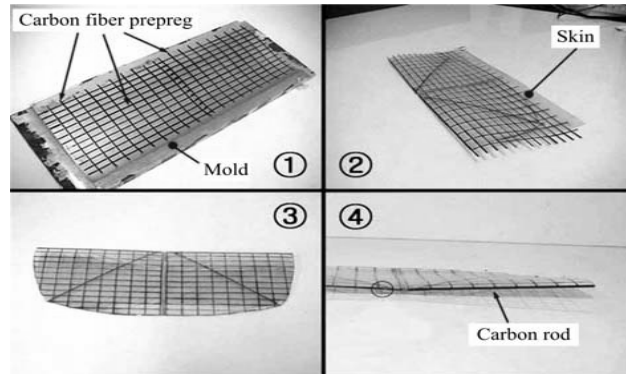


Fig. 5: Cell-type wing made up with composite material.

2.3 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, shown in Figure 6.

**Fig. 6:** Airfoil EH3012.**Fig. 7:** Procedures of bio-mimetic wing fabrication.

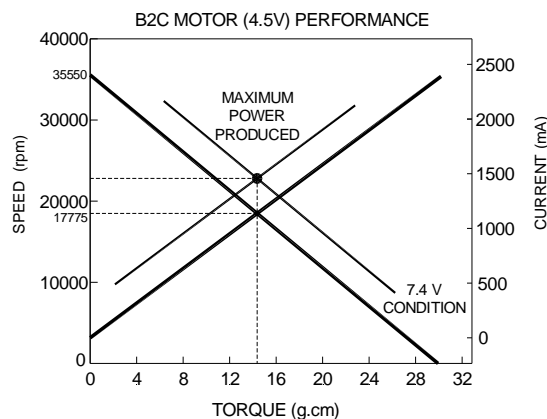
2.4 Fabricating

Here in the paper fabricate the cambered and cell-type wing. The procedure of fabrication is shown using the optimized airfoil shape of the wing that shown in the Figure 7.

3. Transmission Design

3.1 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. The Figure 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 300g-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.

3.2 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 as shown in Figure 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 contra rotation. 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.

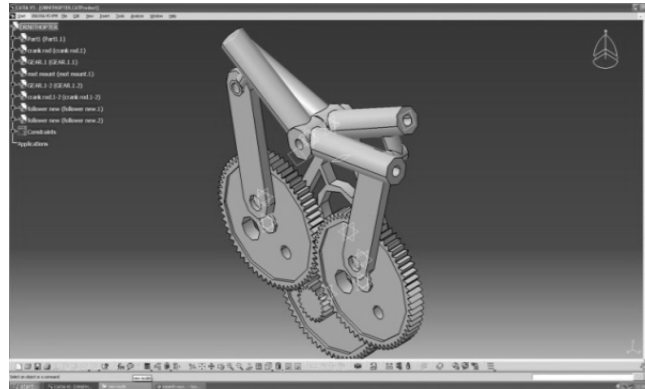


Fig. 9: Concept design of three types of gear box.

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.

3.3 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.

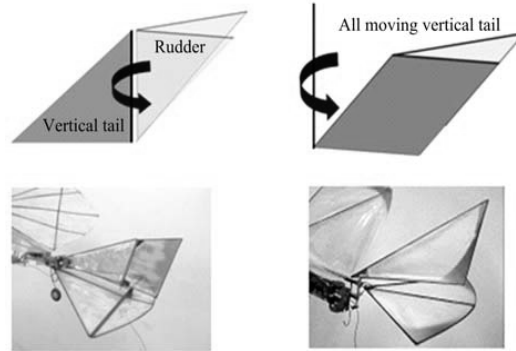


Fig. 10: Vertical tail design.

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 as shown in Figure 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 was installed at -18° to the wing as shown in Figure 11. The horizontal stabilizer was also configured after flight testing to achieve the most efficient shape and placement.

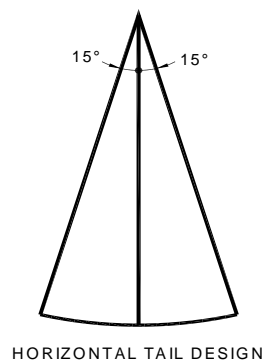


Fig. 11: Horizontal tail design.

4. Prototype Vehicles with Specification

4.1 36 cm Ornithopter capable of Takeoff and landing with Vision Sensor

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 Figure 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.

As like the table the other 4 ornithopter result will be taken out and the result will be compared with the help of all up weight of the ornithopter and the design performance will be optimized using ADMAS software and CFD analysis using the details in the table 1

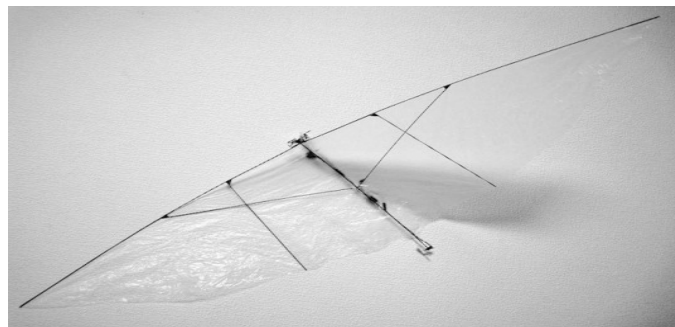


Fig. 12: 36 cm Ornithopter.

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·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		

Component part Mass(g), Wing span 36 cm, Motor 6.09, Wing area 432sq. cm, Battery 10.2 Weight 50 g, Speed controller 1.22, Wing loading 0.115 g·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 minutes.

5. Conclusion

Takeoff and landing system design and configuration: In this we have 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. It is highly complicated to make the ornithopter fully autonomous since we need to find the inertial dynamics of the UAV to find out the minimal vibration location where only we can fix our autopilot. And finding the position of the ornithopter using the local GPS (IMU) is highly complex. Therefore here we are going to use the 3D motion camera for formation control of ornithopter in future.

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