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Technical Notes

Experimental Investigation on Aerodynamic Performance of Gliding Butterflies

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I. Introduction

RECENTLY, the development in micro technology has accelerated the research on micro air vehicles (MAVs). In particular, insectlike MAVs have attracted considerable attention. The past investigations demonstrated that a flying insect not only generates sufficient lift, but also controls the flight with great precision [1,2]. According to wing-beat frequency and wingspan length, insect flight can be sorted into two categories. The first category is the flight with high wing-beat frequency epitomized by insects with small-scale wingspans such as bees and flies, and the other is the flight with low wing-beat frequency exemplified by insects with large-scale wingspans such as butterflies and hawkmoths.

Some dimensionless parameters of bees and butterflies are presented to elucidate the different categories. By contrast with the Reynolds number of 2000 for bees, the Reynolds number of butterflies is nearly 10^4 based on the definition for a flapping wing and 2×10^4 for a fixed wing. The span-based reduced frequency of bees is seven times higher than that of butterflies and the aspect ratio is five times higher. Therefore, the investigation on butterfly flight has attracted great attention in the last century, and plentiful kinematic parameters (such as flapping angle and body angle) have been revealed [3–5].

To clarify the high-lift mechanism of butterfly flight, Srygley and Thomas [6] investigated the flow structure over a free-flying Red Admiral butterfly in a wind tunnel by smoke–wire flow visualizations. The results indicated that some aerodynamic mechanisms including wake capture, two different types of leading-edge vortex, and active and inactive upstrokes were applied to generate more lift in successive strokes when the butterfly took off, maneuvered, and landed. However, these mechanisms were avoided in a steady forward flight. Senda et al. [7] calculated the aerodynamic force of the butterfly, which was considered as a rigid-multibody system by Lagrangian method. Meanwhile, they also measured the aerodynamic force with a micro load cell to substantiate the validity of their mathematical model.

Up to now, the flow structures of butterflies have not been attached such importance to as their flight motions. However, it is found that when a butterfly flies forward in a windless stream, it always flaps wings for several times and then keeps them with a constant dihedral angle to glide for a distance steadily. The flight combining flapping and gliding motions improves the flight efficiency greatly. In fact, the gliding motion does not occur in the flight of a small-scale insect, and it is featured profoundly in a butterfly flight, even more so than the flapping motion. The flow structure of gliding motion may be the primary aerodynamic mechanism for migratory butterflies. Therefore, research on the gliding flight of butterflies may shed some light on the flight mechanism of large-scale flying insects.

In addition, the flapping-wing MAVs already succeeding in flying automatically or under control share in the similar Reynolds number with large-scale butterflies. If the gliding motion is applied in the flight of these MAVs, their flight efficiency and endurance will be enhanced greatly. But the gliding motion of natural butterflies may be not epitomized easily into only one wing position, because they glide with different dihedral angles, depending on ambient conditions and their behavioral requirements. Furthermore, the butterflylike MAVs are different from the natural butterflies in wing flexibility, configuration, etc. Therefore, we would like to investigate the gliding flight of butterflies in consideration of attack angle, sweep-forward angle, and dihedral angle, together in the reasonable range of Reynolds numbers. The optimum position of wings generating higher lift and lower drag will be applied in the flight of butterflylike MAVs. However, we used a simplified butterfly model in the preliminary work. Because butterflies take advantage of the gliding motion in a windless stream with low turbulence intensity, measurements in a conventional steady water channel or wind tunnel can be used to investigate the flow structure and aerodynamic characteristic of gliding motion.

Hu et al. [8] used hydrogen bubble visualizations to observe the flow structures over a simplified model of *Papilio ulysses* (one species of migratory butterfly) at $Re = 9 \times 10^3$, and the variation of flow structures with angle of attack was investigated in detail. A new type of leading-edge vortex, shown in Fig. 1a, was observed that might provide high lift for the weight support of butterflies in a gliding flight. Further effort was made to explore the effect of wing shape on the flow structures and then led to the discovery that leading-edge radius could affect the shape and the strength of leading-edge vortex [9]. As shown in Fig. 1, the vortex core of *Danaus plexippus* was straighter and more concentrated. The breakdown location of *Danaus plexippus* was more downstream than that of *Papilio ulysses*. These results indicated that *Danaus plexippus* had a stronger leading-edge vortex, which should generate higher lift. Moreover, *Danaus plexippus* has weaker wing-tip vortex than *Papilio ulysses*, which might lead to lower drag coefficient.

In this Note, force measurement and oil flow visualization are carried out in a wind tunnel to study the aerodynamic characteristics and flow structures of two species of migratory butterfly, *Papilio ulysses* and *Danaus plexippus*. In nature, *Papilio ulysses* has a larger wingspan length (150 mm) and a shorter migration distance than *Danaus plexippus* (100 mm). By comparing the aerodynamic characteristics of the two experimental models of the insects, the lift-to-drag ratio of *Danaus plexippus* is twice as large as *Papilio ulysses* at a moderate angle of attack. Furthermore, the relationships between aerodynamic characteristics and flow structures are discussed.

II. Experimental Setup

The force measurement and oil flow visualization have been conducted in a low-speed recirculation wind tunnel in Beijing University of Aeronautics and Astronautics. The tunnel has a 1.45-m-long open working section with an elliptical cross section of $1.02 \text{ m} \times 0.76 \text{ m}$ at the inlet and $1.07 \text{ m} \times 0.81 \text{ m}$ at the outlet. The maximum freestream speed can reach 50 m/s and the turbulence intensity is less than 0.3%.

The simplified models tested here are derived from *Papilio ulysses* and *Danaus plexippus* with different wing shapes. The two

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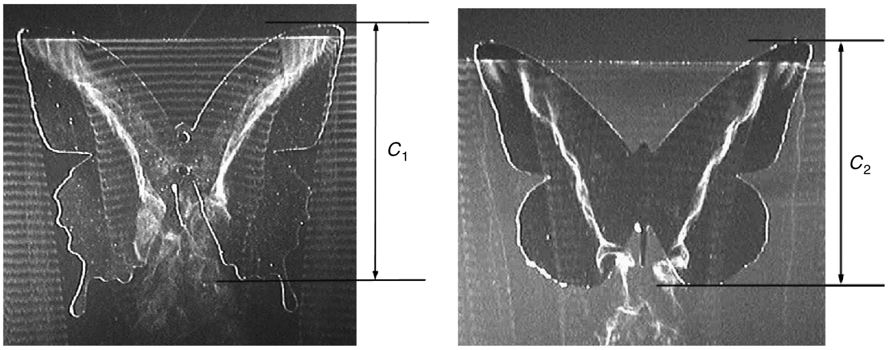
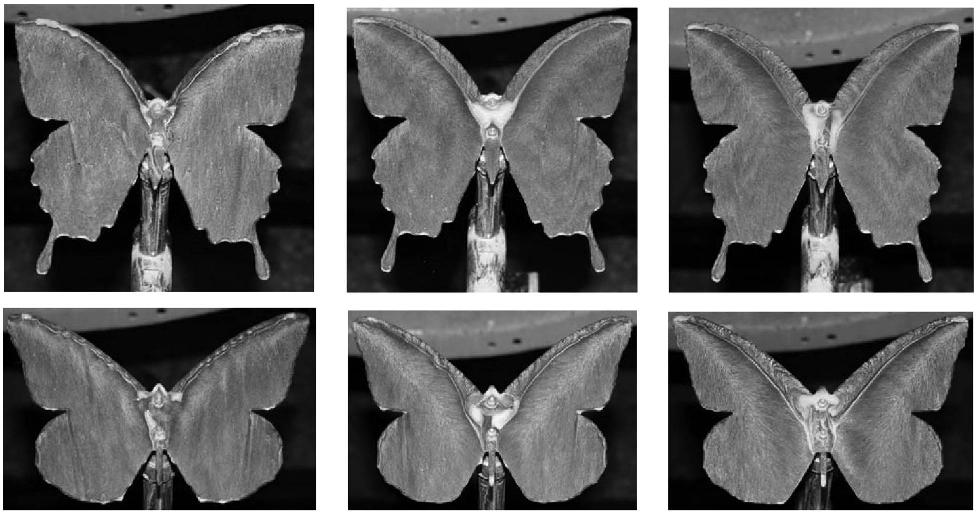


a) ***Papilio ulysses*** **b)** ***Danaus plexippus***

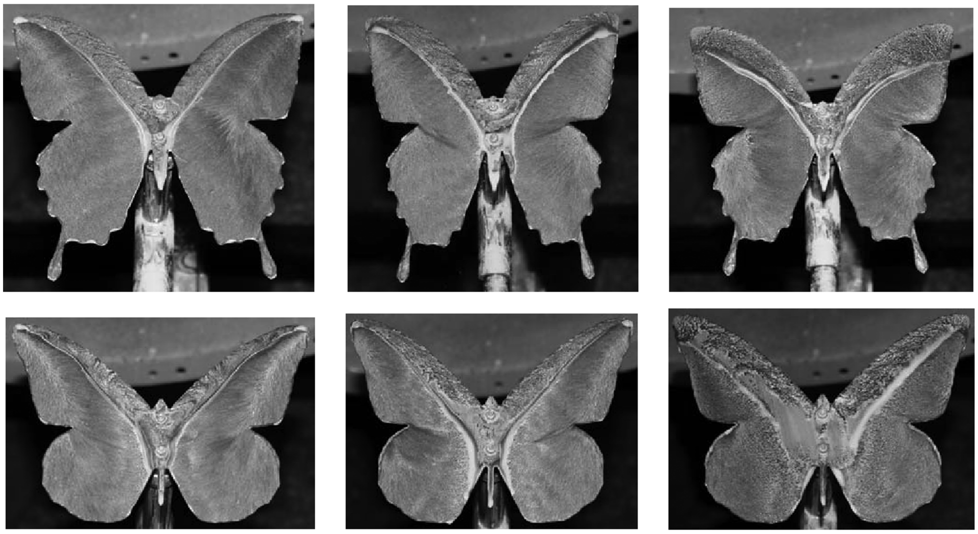
Fig. 1 Leading-edge vortex of butterfly model ($\alpha = 8°$) (c_1 and c_2 are maximum chord lengths of models for *Papilio ulysses* and *Danaus plexippus*, respectively).

butterflies are magnified proportionally to obtain the experimental models with the same wingspan length of $L = 200$ mm. Both models have a square leading edge with a thickness of $\theta = 1$ mm. As shown in Fig. 1, the maximum chord lengths c for the models of *Papilio ulysses* and *Danaus plexippus* are $c_1 = 178$ mm (without including the tails) and $c_2 = 146$ mm. Based on the freestream velocity of $U = 25$ m/s, the Reynolds numbers are 3.0×10^5 and 2.5×10^5, respectively.

The force measurement is undertaken using a force sensor with a measuring range of 3 kg and accuracy of 3% for full load. Before testing, the calibration of force sensor is checked through the application of known weights. In the experiment, the butterfly model is supported horizontally from the pressure surface by the force sensor installed between the model and the support. The angle of attack of butterfly model ranges from $\alpha = -4°$ to $\alpha = 30°$ with a step of 1°. In the oil flow visualizations, the angle of attack increases in 2°.



a) $\alpha = 4°$ **b)** $\alpha = 8°$ **c)** $\alpha = 12°$



d) $\alpha = 16°$ **e)** $\alpha = 20°$ **f)** $\alpha = 22°$

Fig. 2 Oil flow picture: *Papilio ulysses* (top rows) and *Danaus plexippus* (bottom rows).

Other experimental conditions coincide with those of force measurement.

Since the force sensor below the butterfly model measures the aerodynamic forces in the body-axis system, the aerodynamic coefficients need to be transformed from the body-axis system to the wind-axis system in order to present the aerodynamic performance. The angle of sideslip is taken to be zero in this work, so transformation formulas are shown as Eq. (1):

$$C_L = C_{LB}\cos\alpha - C_{DB}\sin\alpha \qquad C_D = C_{LB}\sin\alpha + C_{DB}\cos\alpha \tag{1}$$

where C_L and C_D represent lift coefficient and drag coefficient in the wind-axis system, respectively; C_{LB} and C_{DB} represent lift coefficient and drag coefficient in the body-axis system, respectively; and α is angle of attack.

III. Aerodynamic Performance and Flow Structure Analysis

In nature, the two migratory butterflies in this Note fly in the turbulent transition region with the Reynolds number of 10^4, where the sharp leading edge is acting as a turbulator to accomplish a premature transition to turbulence for butterflies [10]. Therefore, due to the sharp leading edge of the butterfly models ($\theta/c < 1\%$), the flow structures on the suction surface are independent on the Reynolds number in the range tested. For instance, Fig. 1 and 2b show the same conclusion that the leading-edge vortex of *Danaus plexippus* is stronger than that of *Papilio ulysses* and closer to the model side at $\alpha = 8°$. It is obvious that the oil flow visualization in this work is consistent well with the previous hydrogen bubble visualization [9], though the Reynolds numbers are different ($Re = 9 \times 10^3$ in the water channel and $Re = 3.0 \times 10^5$ in the wind tunnel). So the results of force measurement in the work could be applied to explain the aerodynamic characteristic in the gliding flight of natural butterflies.

First, the aerodynamic characteristic is examined with angle of attack. Second, the effect of flow structure on the aerodynamic performance in a gliding flight is investigated based on the results of force measurement and flow visualization. In addition, the differences between the two butterfly models are also discussed.

A. Lift Coefficient

As shown in Fig. 3, when the lift coefficient of *Papilio ulysses* increases with angle of attack, two reductions in lift-curve slope appear at $\alpha \approx 4$ and $\approx 20°$, respectively. In the oil flow visualization and the hydrogen bubble visualization [9], the weak leading-edge vortex emerges on the suction surface at $\alpha \approx 4°$ (Fig. 2a). For $\alpha < 4°$, the attached flow occupies almost the whole suction surface, except for the separation bubble, which is close to the leading edge in a small area. The butterfly models have a square leading edge. When the angle of attack is zero, the flow separated at the sharp leading-edge corner can reattach to the lateral wall to form the leading-edge separation bubble, which is similar to the flat plate with a square leading edge [11].

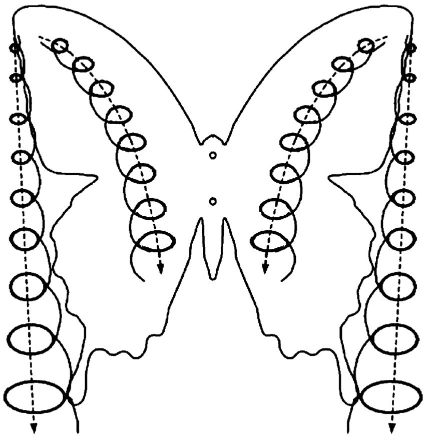


Fig. 4 Sketch of leading-edge vortex and wing-tip vortex.

As the angle of attack increases, the separation bubble evolves into the leading-edge vortex resulting in the slowdown of low-pressure increment on the suction surface. Therefore, the lift-curve slope declines slightly at $\alpha \approx 4°$. The leading-edge vortex and the wing-tip vortex strengthen with angle of attack, and their sketches are shown in Fig. 4. The leading-edge vortex breaks down at $\alpha \approx 22°$ in the oil flow visualization and the hydrogen bubble visualization [8,9]. The lift-curve slope of *Papilio ulysses* decreases again, but the lift coefficient continues to increase.

Just as the reduction in lift-curve slope of *Papilio ulysses* at $\alpha \approx 4°$, the first slope of *Danaus plexippus* decreases at $\alpha \approx 2°$. Although the lift-curve slope reductions of the two butterflies occur for the same reason, *Danaus plexippus* shows the first reduction at $\alpha \approx 2°$, which is lower than *Papilio ulysses* at $\alpha \approx 4°$. The result of hydrogen bubble visualization [9] indicated qualitatively that the leading-edge vortex of *Danaus plexippus* is stronger than that of *Papilio ulysses* at $\alpha \approx 4°$. It means that the leading-edge vortex of *Danaus plexippus* may be visible at lower angle of attack, and this can be used to explain why the reduction in lift-curve slope of *Danaus plexippus* occurs at $\alpha \approx 2°$. *Danaus plexippus* stalls at $\alpha = 20°$, while the leading-edge vortex breaks down on the suction surface at $\alpha \approx 22°$ shown in Fig. 2f. Beyond angle of stall, the slight decrease of lift coefficient indicates a better stall characteristic at high angle of attack.

In this experiment, the range of angle of attack is restricted by the experimental mechanism so that the angle of stall and the maximum lift coefficient of *Papilio ulysses* are not presented in Fig. 3. Nevertheless, it can be deduced that *Papilio ulysses* has larger angle of stall and higher maximum lift coefficient than *Danaus plexippus*. More significantly, *Danaus plexippus* has much higher lift coefficient before stalling, which is expected for a natural butterfly

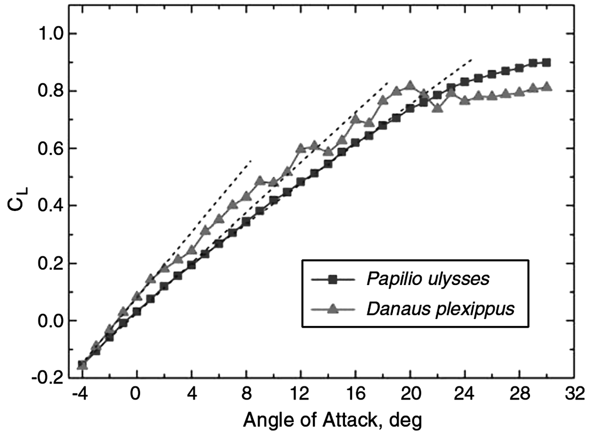


Fig. 3 Lift coefficient.

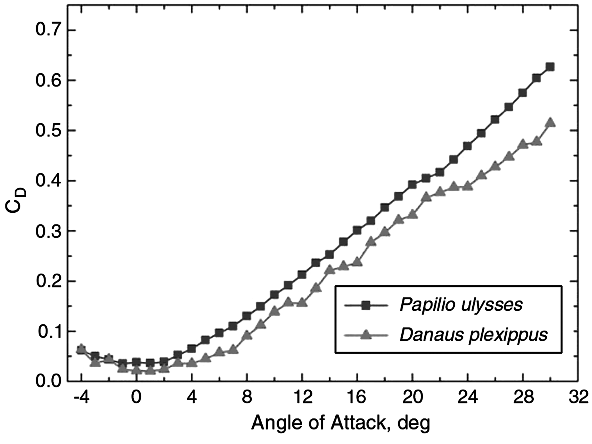


Fig. 5 Drag coefficient.

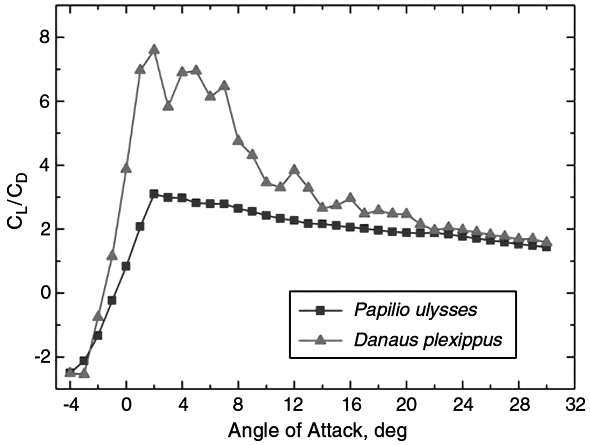


Fig. 6 Lift-to-drag ratio.

at low and moderate angles of attack in a gliding flight. As shown in Fig. 2, the leading-edge vortex of *Danaus plexippus* is stronger than that of *Papilio ulysses* for $\alpha \leqslant 20^\circ$. This is consistent with the result of hydrogen bubble visualization [9] and accounts for why *Danaus plexippus* has higher lift coefficient.

B. Drag Coefficient

The drag coefficient of *Papilio ulysses* is larger than that of *Danaus plexippus* shown in Fig. 5. The hydrogen bubble visualizations [9] presented qualitatively that *Papilio ulysses* has the stronger wing-tip vortex, and hence the larger induced drag.

C. Lift-to-Drag Ratio

From the aforementioned discussions, it can be concluded that *Danaus plexippus* has higher lift coefficient and lower drag coefficient than *Papilio ulysses* at low and moderate angles of attack. Therefore, *Danaus plexippus* is superior to *Papilio ulysses* in the lift-to-drag ratio. In Fig. 6, the lift-to-drag ratio of *Danaus plexippus* increases rapidly to the maximum value of 7.6 at $\alpha = 2^\circ$, while the maximum value of *Papilio ulysses* is only 3.1 at $\alpha = 2^\circ$. Furthermore, the lift-to-drag ratios of *Danaus plexippus* are twice as large as *Papilio ulysses* in the range of $1^\circ \leq \alpha \leq 7^\circ$. Figure 2 shows that the leading-edge vortex of *Danaus plexippus* is more substantial and concentrated than that of *Papilio ulysses*. Wing-tip vortex swirls in a smaller area are shown in Fig. 1. These flow structures give rise to the higher lift-to-drag ratio for *Danaus plexippus* at a moderate angle of attack. Finally, the two curves of lift-to-drag ratio nearly converge for $\alpha > 22^\circ$.

IV. Conclusions

The experiments of force measurement and oil flow visualization are performed to investigate the relationships between aerodynamic performance and flow structures of two migratory butterflies in a gliding flight. The following conclusions are made: For the butterfly models tested in this work, their lift-curve slopes decline slightly at the low angle of attack due to the transform of flow structure from the separation bubble to the leading-edge vortex. The leading-edge vortex of *Danaus plexippus* is visible at $\alpha \approx 2^\circ$, while *Papilio ulysses* is at $\alpha \approx 4^\circ$. Therefore, the reduction in lift-curve slope of *Danaus plexippus* occurs at lower angle of attack.

Danaus plexippus has higher lift coefficient and lower drag coefficient than *Papilio ulysses* before stalling, which leads to the lift-to-drag ratio of *Danaus plexippus* being twice as large as *Papilio ulysses* at a moderate angle of attack. The results could explain the flight superiority of *Danaus plexippus*. It is hoped that this work will contribute to the development of butterflylike MAVs.

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