곤충과 새의 비행방법

How Birds and Insects Fly

홍 영 선*
Young-Sun, Hong

ABSTRACT

Using steady state aerodynamic theories, it has been claimed that insects and birds cannot fly. To make matters worse, insects and birds fly at low Reynolds numbers. Therefore, a recurring theme in the literature is the importance of understanding unsteady aerodynamic effect and how the vortices behave when they separate from the moving surface that created them. In flapping flight, birds and insects can modify wing beat amplitude, stroke angle, wing planform area, angle of attack, and to a lesser extent flapping frequency to optimize the generation of lift force. Some birds are thought to employ two different gaits(a vortex ring gait and a continuous vortex gait) and unsteady aerodynamic effect(Clap and fling, Delayed stall, Wake capture and Rotational Circulation) in flapping flight. Leading edge vortices may produce an increase in lift. The trailing edge vortex could be an important component in gliding flight. Tip vortices in hovering support the body weight of the hummingbirds. Thus, this study investigated how insects and birds generate lift at low Reynolds numbers. This research is written to further that as yet incomplete understanding.

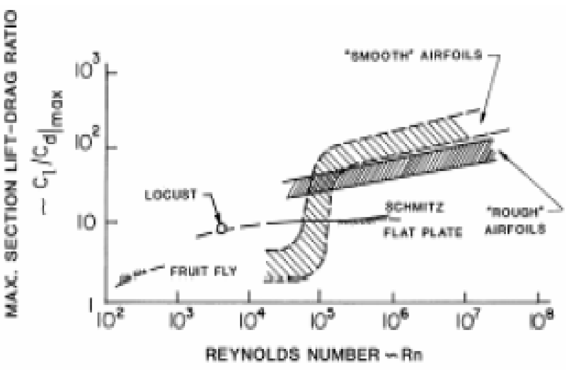
주요기술용어(주제어) : Flapping Wing, Bird, Insect, Vortex, Low Re

1. Introduction

Aerodynamicists have used the some theories to explain how airfoils generate lift. The principle of equal transit times is often mistakenly asserted as the manner in which a wing generates lift. This principle states that the pressure over the top of the airfoil creates a region of pressure lower than the bottom of an airfoil because flow over the curved upper surface would have to have greater velocity than that at the lower surface which is more flat. In reality, the principle of equal transit times holds only for a symmetrical wing not generating lift. A perhaps more plausible reason for why an airplane wing generates lift is because of Newton's third law which states "for every action there is an equal and opposite reaction". The airfoil changes the direction of the air. It sends a stream of air in the opposite

† 2006년 12월 19일 접수~2007년 2월 9일 게재승인
* Major, Korea Air Force Headquarter, KyeRyong, ChungNam
주저자 이메일 : young_sun_hong@yahoo.com

direction to the lift, in order to send the wing upward. The aerodynamic force generated via conventional mechanisms is insufficient to explain the nature of insect flight. Insects and birds fly at low Reynolds numbers. The performance of low Reynolds number airfoils is entirely dictated by the relatively poor separation resistance of the laminar boundary layer. Laminar separation bubbles occur on the upper surface of most airfoils at Reynolds numbers about 50,000. These bubbles become larger as the Reynolds number decreases, usually resulting in a rapid deterioration in performance, i.e., substantial decrease in L/D(Figure 1). Therefore, airfoil performance deteriorates rapidly as the Reynolds number decreases below 100,000. Above Reynolds number of 200,000, airfoil performance improves significantly and there is a great deal of experience available from large soaring birds, large radio controlled model airplanes, human powered airplanes, etc. Therefore, much existing research has attempted to show how insects and birds produce enough lift. In so doing they have found that insects and birds use specific mechanisms or tricks to generate more lift. This research also tried to find specific mechanism or technique to generate enough lift during flapping flight.



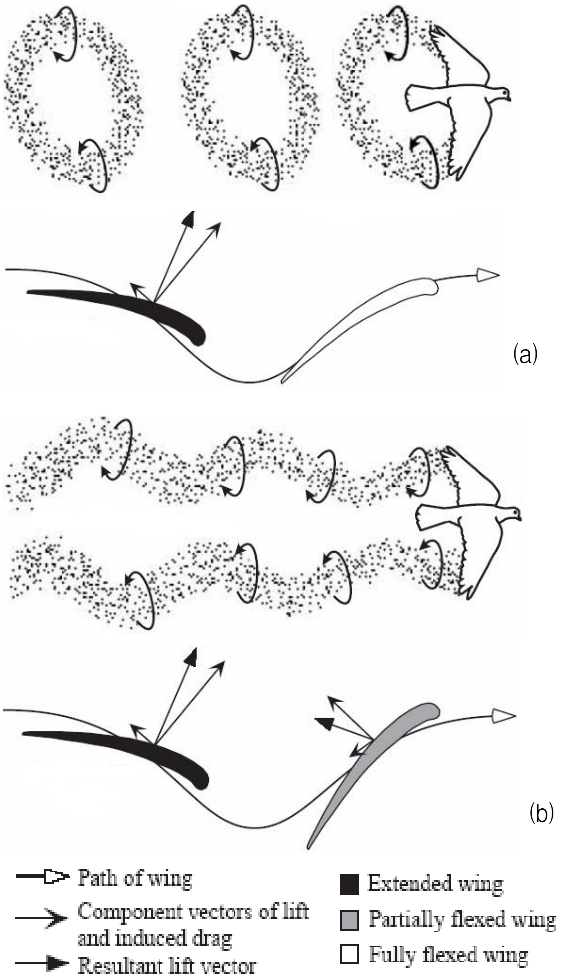
[Figure 1] Maximum lift and drag ratio due to Reynolds number[1]

2. Gait Selection

Birds are thought to employ two different gaits in flapping flight, a vortex ring gait in slow flight and a continuous vortex gait in fast flight. A vortex ring gait is also employed in slightly faster flight in birds with shorter wings and lower aspect ratio wings. A continuous vortex gait is used in faster forward flight and by birds with relatively long, higher aspect ratio wings. In slow speed flight birds are thought to employ the vortex ring gait in which each downstroke produces a single vortex ring shed from the wing into the wake at the end of the downstroke. The bound vortex decays to zero at the end of the downstroke. The upstroke appears to be aerodynamically inactive at slow speeds, with little or no vortex shedding and lift generation(Figure 2(a)). In faster flight, several bird species employ a continuous vortex gait in which each wingtip sheds a separate vortex trail during both the upstroke and downstroke(Figure 2(b)). This implies that a constant bound circulation is maintained over the airfoil(wing) throughout the entire wing beat cycle and that lift is generated during both the upstroke and downstroke. In the vortex ring gait, the vortex elements are elliptic or near circular, while in the continuous vortex gait the vortex elements closely follow the path of the wingtip.

3. Unsteady Aerodynamics of Flapping Wings

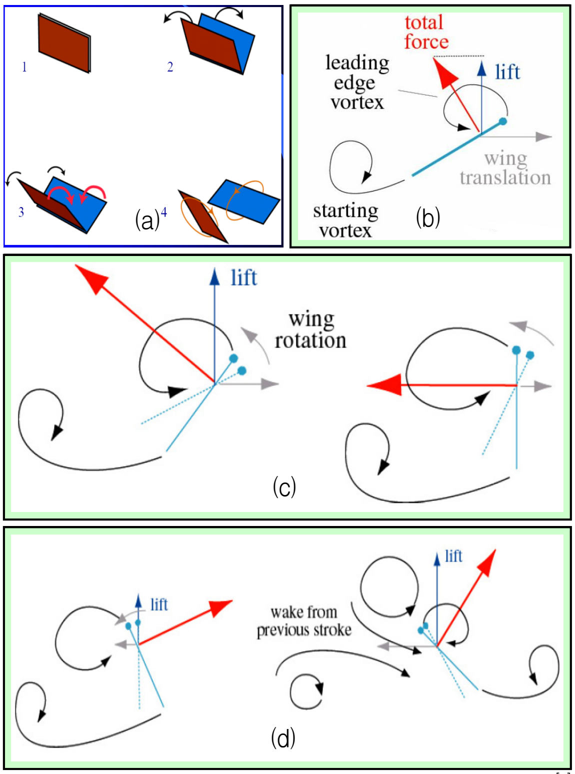
The wing stroke of an insect is typically divided into four kinematic portions : two translational phases(upstroke and downstroke), when the wings sweep through the air with a high angle of attack, and two rotational phases



[Figure 2] Vortex ring gait and continuous vortex gait[2] (a) Vortex ring gait. Lift is produced only during the downstroke, providing positive upward force and forward thrust. (b) Continuous vortex gaits. Lift is produced during both the upstroke and the downstroke. The downstroke produces a positive upward force and forward thrust; the upstroke produces a positive upward force and rearward thrust. Partial flection of the wing during the upstroke reduces the magnitude of the rearward thrust to less than that of the forward thrust produced during the downstroke, providing net positive thrust per wingbeat.

(pronation and supination), when the wings rapidly rotate and reverse direction. One unsteady effect thought to generate lift is a rotational mechanism termed the *Clap and fling*[3]. The wings clap together at the end of the upstroke and peel apart at the beginning of the downstroke, rotating about their trailing edges and producing an initial strong bound vortex on each wing of equal and opposite sign. This fling induced circulation can be large for high rotational velocities and enhance the downstroke lift(Figure 3(a)).

Delayed stall[5] is the result of the translational motion of the wing and it depends only on the wing translational velocity and angle of attack. The insect sweeps its wing forward at a high angle of attack, cutting through the air at a steeper angle than a typical airplane wing. At such steep angles, a fixed wing aircraft would stall, lose lift and the amount of drag on the wing would increase. An insect wing creates a Leading Edge Vortex(LEV) that sits on the surface of the wing to create lift(Figure 3(b)). *Rotational circulation*[6] results from the interaction of the translational and the rotational velocity of the wing. At the end of a stroke, the insect wing rotates backward, creating backspin that lifts the insect up, similar to the way backspin can lift a tennis ball. The wing's own rotation possibly serves as a source of circulation to generate an upward force(Magnus effect). Forces are dependent upon the direction of wing rotation (Figure 3(c)). *Wake capture*[6] is a result of the interaction of the wing, when it inverts its motion, with the wake generated in the previous stroke. The wing benefits from the shed vorticity of the previous stroke. As the wing moves through the air, it leaves vortices of air behind it. When the insect rotates its wing for a return stroke, it cuts into its own wake, capturing enough energy to keep itself aloft. Dickinson[6](1999) states that



[Figure 3] Unsteady aerodynamics of flapping wing[4] (a) Clap and fling is that the wings clap together at the end of the upstroke and peel apart at the beginning of the downstroke (b) Delayed stall causes the formation of a leading edge vortex that reduces pressure over the wing. (c) Rotational circulation is created when the insect rotates the angle of its wings (dotted line), creating a vortex similar to that of putting "backspin" on a tennis ball. At its completion(left), the maneuver also results in a powerful force propelling the insect forward. (d) Wake capture gains an insect added lift by recapturing the energy lost in the wake. As the wing moves through the air, it leaves vortices, of air behind it(left). If the insect rotates its wing(dotted line), the wing can intersect its own wake and capture its energy in the form of lift(right).

insects can get lift from the wake even after the wing stops(Figure 3(d)). This wake capture was most clearly manifested by the generation of lift at an angle of attack of 0 degrees. To minimize energy expenditure during flight the animal should optimize the generation of the vortex wake, which means that it is possible that birds that migrate long distances use some mechanisms or tricks to produce an optimized vortex to conserve energy.

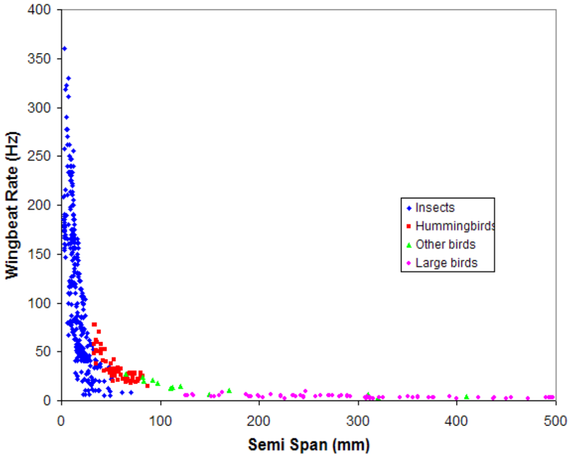
4. Flapping Frequency and Amplitude

There is a frequency variation among different species and within each species of birds and insects. There is a consistent trend in these variations, which means that large birds that have long wings appear to operate in the lower frequency regime, and small insects that has short wings use higher flapping frequencies to fly.

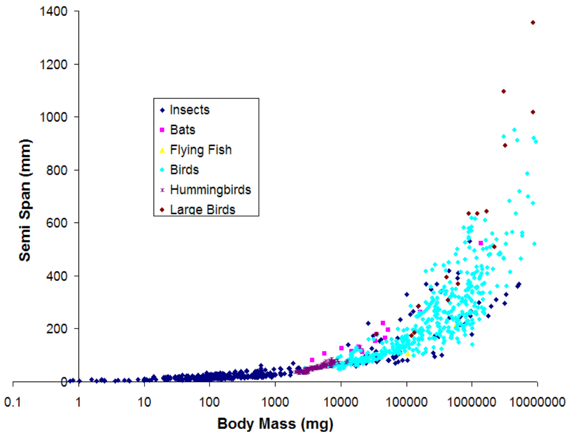
Figure 4 demonstrates that the span of the wings of over 1000 birds and insects taken from Greenwalt[7](1962) correlate rather well with flapping frequency and reasonably well with body mass. These relationships could potentially be purely coincidental, however, there is also a good chance they could be indicative of the relative importance of the spanwise direction in the aerodynamics of birds and insects. There are no similar correlations for the chord lengths or wing areas of birds and insects as can be seen in Azuma[8](1992).

For an bird or insect in flight, the Strouhal number is determined by the frequency (f) of wing strokes, multiplied by the amplitude (Φ) of the wing, divided by the animal's forward speed (U_∞) through the air.

$$St = \frac{f \cdot \Phi}{U_\infty} \tag{1}$$



(a)



(b)

[Figure 4] Correlation between wingbeat frequency, wing semi span and total animal mass show that span could be a dimension of interest[9]. (a) Wing beat frequency versus wing semi span of various insects and birds (b) Wing semi span versus body mass of various animals including insects, bats, birds.

St is known to govern a well defined series of vortex growth and shedding regimes for airfoils undergoing pitching and heaving motions. This seems to be true for dolphins, sharks and bony fish, which swim at 0.2~0.4[10]. Triantafyllou & Gopalkrishnan[11](1991) also showed that optimal flapping occurs when the Strouhal number is in the range of 0.2~0.3. However, Wang[12](2000) explained that an optimal Strouhal number alone does not select an optimal frequency. Jones also mentioned that the Strouhal number is not reliable to validate the phenomena of flapping.

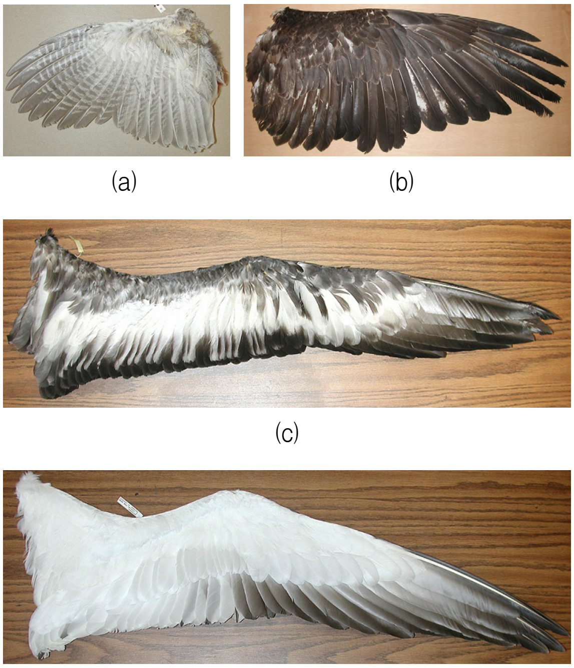
Gursul and Ho[13](1992) observed that the lift coefficient peaks at a certain frequency, and argued that this frequency could be related to the length scale of the Leading Edge Vortex. Rayner[14](1991) shows that amplitude increases and frequency decreases as flight speed increases. Wingbeat amplitude tends to decrease with speed : by 20~30° for bumblebees[15] and by approximately 15° for hawkmoths[16]. Results for other insects either support this trend or suggest that amplitude remains constant. Birds try to minimize power out using the amplitude of the flapping motion. Alexander[17](2002) reports that locust downstroke duration can be as much as 1.9 times the upstroke. This means the downstroke lasts 90% longer than the upstroke. Albatross have a downstroke vs upstroke ratio of 1.06 and a bat has a ratio of 2.1 in slow flight. This observation is characteristic of most flying animals and is largest in slow flight. Therefore insect and birds also generate more lift force during the downstroke. Hummingbird flapping flight shows that the angular velocity of the wing is slightly less during the upstroke(146±15rad/s) than during the downstroke(196±26rad/s)[18]. The downstroke usually entails more than 50% of the wingbeat cycle for both the magpie and the pigeon[19].

5. Wing Shape and Wing Loading

A. Wing Shape

Birds have various wing planform shapes.

For example, pheasant wings(Figure 5(a)) which have a low aspect ratio(AR) of around 3 to 6 can impulsively produce the lift for flight, and pheasant wings are quite adequate for relatively slow powered flight, but not good for gliding. Most birds that have low AR wings use slots to get more lift. The maximum lift coefficient is largely independent of the aspect ratio for low aspect ratio wings. AR's between 3 and 6 can fly suddenly and fly slowly under powered flight. They are not as good for gliding. Albatross and gulls(Figure 5(c)) have long, thin wings with an AR of around 13.8 and higher and no tip feathers. These are good for gliding over the sea, close to the surface, using small changes in wind direction to maximum advantage. Eagles(Figure 5(b)) have broad, long wings with an AR of around 9.3 and the feathers at the ends separate out into primary feathers that help with minute control(like airfoils) while the birds are gliding. These are birds riding high above the ground using a variety of updrafts to avoid flapping. Gannets(Figure 5(d)) have medium length wings with an AR of around 12.5, they also tend to be pointed and swept after the first half. These wings are not suited to take off, but allow for a faster top speed and a little gliding. They are good for long distance migrants.



(a) (b) (c) (d)

[Figure 5] Four different varieties of wing shapes. (http://www2.ups.edu/biology/museum/wingphotos.html) (a) Pheasant (b) Bald eagle (c) Albatross (d) Gannet

Birds that feed in flight and long distance migrants have low camber wings(flat profile), high aspect ratio, taper to a slender tip(no slot) and pointed tips to minimize drag. Generally the wings that can fly with high speed has the shape of a long pointed wing, high AR and no slot with swept back primaries.

Wing shape affects the distribution of circulation across the wingspan, and hence the span efficiency, lift and induced drag. Rayner[14](1991) explained that the wingtip shape also has a significant effect on the wake and emphasized that the wing shape is important to decide the strength of spanwise flow. The continuous vortex gait is used in cruising or steady fast flight by animals with relatively long or high aspect ratio wings; it does not occur in species with shorter or more rounded wings and is not used in slow flight.

B. Wing Loading

The long tailed hornbill has an AR of 4.65 and a wing loading of 0.175kg/m^2, and the yellow casqued waffled hornbill has an AR of 4.53 and wing loading of 0.709kg/m^2. The yellow casqued

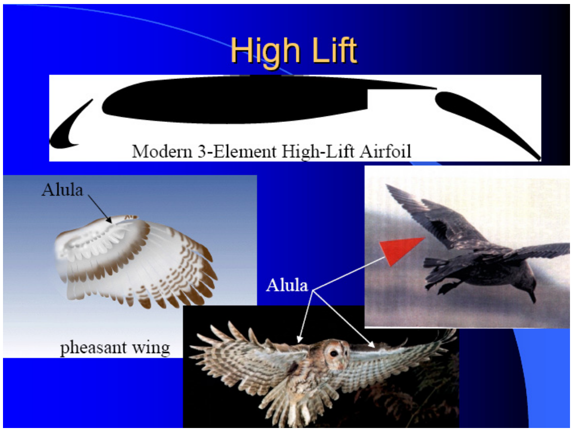
[Table 1] Wing loading versus cruising speed of various birds[20](Shyy, 1999)

Name	W/S (N/m^2)	V (m/s)
Common Tern	23	7.8
Black Skimmer	34	9.4
Fulmar	66	13.2
Sooty Albatross	82	14.7
Wandering Albatross	140	19.2

waffled hornbill is much heavier and more labored flight. High wing loading increases minimum flight speed and glide speed, on the other hand low wing loading allows for a slow glide, take off and landing(Table 1).

6. Flow Control Techniques

Birds and bats can flex their wings to reduce drag during the upstroke and they can twist the wings to change the angle of attack and vary the profile. Shyy et al[21](1997) studied the influence of airstream fluctuation on a single membrane airfoil compared to a rigid one on the lift to drag ratio and they found that a flexible airfoil can adjust its curvature in accordance with the velocity fluctuation. The upturned tip feathers effectively spread the trailing vorticity over a large vertical area, lower the effective downwash velocity and reduce the overall induced drag. Tucker[22](1993) concluded using a natural feathered wingtip and an artificial feathered wingtip, that the slotted tips of bird wings reduce the induced drag. Most birds that have low AR wings use slots to get more lift. Slotted tips do increase the profile drag of the wing, however at the low speed of most of these birds induced drag and lift is more important. Kokshaysky[23](1979) and Lighthill[24](1973) suggested that the main function of the separated primary feathers in bird wingtips is to allow an increase in the effective angle of attack without stall, much like a multi slotted wing. The tip feathers(Figure 6(b)) simply increase the total lift coefficient rather than reduce the drag. In other words, the manipulation of the wingtip vortex can effect the generation of lift. Cone[25](1962) found that a branched tip design increased the effective aspect ratio over a flat wing by 20 to 30%. Tucker[22](1993) used flow visualization



(a)

(b)

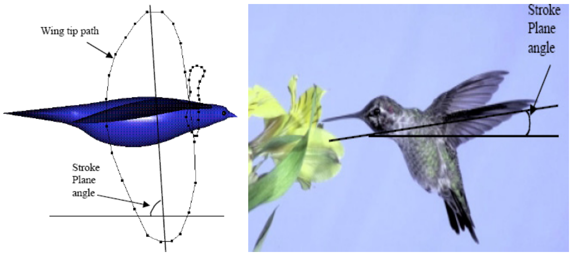
[Figure 6] Alula and bird's slotted wingtip contributing to generate lift. (a) Alula (b) Slotted wingtip[5] methods to show that the separated primary feathers of a Harris' hawk wing achieved a span efficiency of approximately 1.3 by spreading the vortex cores behind the wingtip; for this mechanism to work effectively, it is essential that the wingtip feathers be splayed vertically. An additional high lift device used in flapping wing animals is the alula(Figure 6(a)). The alula has the same function as a multi element airfoil in fixed wings. Splitting feathers serves almost the same purpose as winglets. A serrated leading edge feather like a V shape wing and a flexible material can generate more lift force. Birds also constantly twist their wings to attain the appropriate effective angle of attack throughout the entire wing stroke to produce the necessary aerodynamic forces.

7. Camber

Most aircraft and bird wings are cambered in chord to generate more lift at lower angles of attack. The bird wings are highly cambered near the root, but gradually flatten towards the tip. However, this geometry changes due to their aeroelastic structures. The effects of cambering wings in the chordwise sense are well documented. However, the effects of cambering wings in the spanwise direction have not been quantified as yet. Spanwise camber is observed in the flight of most birds, bats and insects. Insects have been found to have up to 4% camber in span[26]. Dudley[27](2000), Pennycuick[28](1972), Combes[29](2002) and Daniel[30](1987) have discussed the advantages of having wings curved in span. Ennos[31](1989) showed that the presence of spanwise bending due to the inertia of flapping wings could produce at least twice as much aerodynamic force as in rigid wings.

8. Stroke Plane Angle

The stroke plane angle is defined as the angle that the stroke plane of the wing makes with the horizontal(Figure 7). The stroke plane angle is nearly vertical for fast forward flight and is nearly horizontal for hovering flight in birds. The stroke plane angle is related to the distribution of aerodynamic force, (more or less thrust or lift, for example). The body is pitched up to a nearly vertical posture in which the wing flaps horizontally, forward speed can be dropped. As flight speed and advance ratio(the ratio of the flight speed to the speed of the wingtip) increase, the body tilts nose down, and finally becomes horizontal; body drag is therefore minimized at high speeds, where it is increasingly important. The stroke plane rotates with the body orientation and eventually reaches an inclination of approximately 40° to the horizontal[32].



(a) (b)

[Figure 7] Stroke plane angle[5]. (a) Definition of the stroke plane angle (b) The stroke plane angle of hummingbird

9. The Vortex Effect

The aerodynamic force generated via conventional aerodynamic lift mechanisms is insufficient to explain the nature of lift force generation in insect flight. An important point to solving the mystery of insect flight is understanding vortex shedding and how the vortices behave when they separate from the moving surface that created them. Insects depend on vortices to keep them aloft, especially when they are hovering. Vorticity is highly dependent on animal size, wing form, and flight speed and kinematics. To minimize energy expenditure during flight the birds should optimize the generation of the vortex wake. In flapping flight, birds and insects can modify wing beat amplitude, stroke angle, wing planform area, angle of attack, and to a lesser extent flapping frequency to optimize the generation of vortices. Birds and insects also have the wings that can be flexible and twisted.

Pennycuick[33](1975) explained that there are three simple rules about vortices. First, a vortex cannot end freely in the fluid. The vortex system consists of a bound vortex on the wing and two trailing vortices, one in each wake behind the wingtips. Second, circulation is conserved.

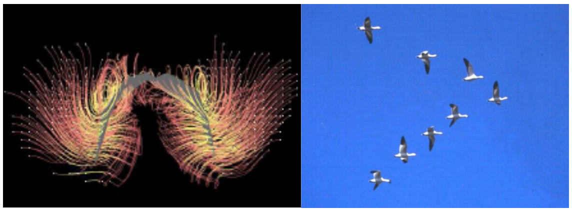
$$\frac{d\Gamma}{dt} = 0 \tag{2}$$

Whenever the strength of the vortex changes by some amount $d\Gamma$, an equal and opposite amount of circulation, $-d\Gamma$, must be shed into the wake, so the sum of circulation about a wing section and all vortices shed into the wake is zero. Third, the amount of energy needed to create a vortex is proportional to its circulation.

An insect wing can create a Leading Edge Vortex(LEV) caused by delayed stall to create lift. A LEV develops along the top of the wing significantly contributing to lift, as the insect wing continues on its downstroke. LEVs may produce an increase in lift. The LEVs are present over the wings from the beginning of the downstroke. The flow visualization results for tethered flapping flight have shown an absence of stalling at the leading edges. The airflow moves smoothly around the leading edges without any formation of a separation vortex. As the wing speed varies along the span, the strength of the unsteady LEV and the lift will also vary. The rotational speed of the wings is higher toward the tips and leads to larger amounts of vorticity in the outboard region of the wing.

Rayner[14](1991) mentioned that the trailing edge vortex can be an important component in gliding flight. One theory is that the trailing edge vortex pair is an important vortex structure in gliding flight since it maximizes vertical momentum while minimizing the energy required generating the wake.

In steady forward flight, however, there has been little evidence of a LEV in V. atalanta butterflies[34]. Yet, wingtip and trailing vortices in steady forward flight are stronger than in hovering flight, because the freestream velocity is thought to play a role in the axial flow of the vortex. Hueso[35](2004) provides the visualized results that emphasize the presence of vortices in simulated airflow around a motion captured bat model(Figure 8(a)). This shows what appears to



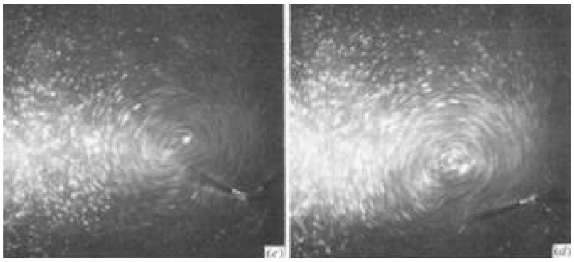
(a) (b)

[Figure 8] The captured vortex in spanwise direction (a) Vortex generation of bat's wing in the spanwise plane[35] (b) 'V' formation of the migrating birds shows that they use continuous wingtip vortices to their advantage(http://www.aerospaceweb.org).

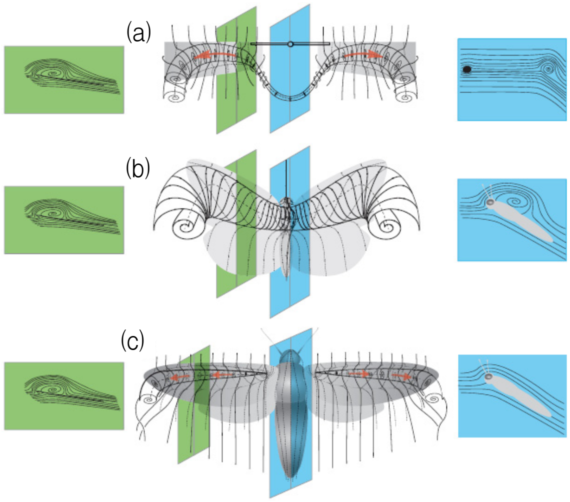
be a vortex in the spanwise plane(streamwise vorticity) captured over the wing in the flight of the bat. The 'V' formation of some migrating birds(Figure 8(b)) validates that steady forward flight of birds also generates wingtip and trailing vortices that they are thought to reclaim to some advantage.

Dickinson(1999) mentioned that when the rotational axis was close to the trailing edge, the model wing could capture vorticity generated during rotation and greatly increase aerodynamic performance. This vortex capture was most clearly manifested by the generation of lift at an angle of attack of 0 degrees. Maxworthy[36](1981), using two mechanical models, clarified the role of this separation and how it can account for the large lift force or, more critically, large lift coefficient that is needed to balance the insect weight. Maxworthy showed that the circulation contained in this separation bubble, also shown in the numerical computation of Haussling, is approximately three times that calculated from the inviscid theory at the instant when the wings begin to part.

The Maxworthy(1979) description from his model experiments based on the 'fling' of the chalcid



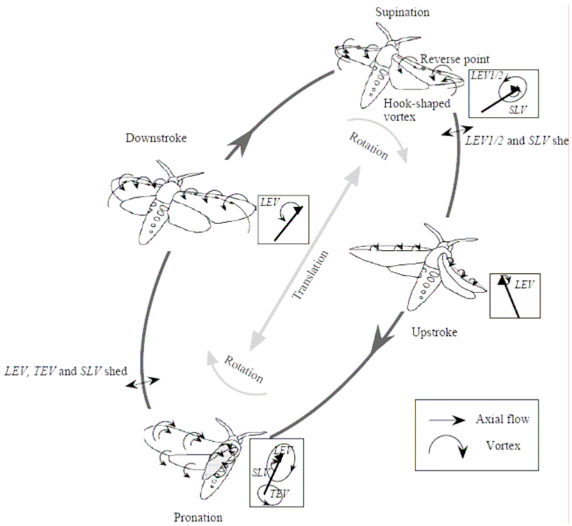
[Figure 9] The vertical flow in two dimension[37]. The vertical flow created by an opening pair of wings in two dimensions. The Reynolds number based on wing chord and opening velocity is about 30 in this sequence.



[Figure 10] The three classes of Leading Edge Vortex(LEV) and tip vortex[39]. (a) The Maxworthy(1979) model (b) The structure described by Luttges(1989) (c) The structure described by Ellington(1996) and Van den Berg(1997). The Maxworthy (1979) description from his model experiments based on the 'fling' of the chalcid wasp Encarsia formosa. The LEV inflects into tip and root vortices on each wing. The tip vortices connect to form a vortex ring behind the model, and the root vortices also connect so that the wake consists of one continuous vortex loop of complex shape. The structure described by Luttges(1989) with a single LEV extending across the thorax of a hawkmoth and inflecting to form both tip vortices. This structure implies a free slip critical point(a 3 dimensional focus) over the centreline of the thorax. The topology is similar to that in (a) except that the root vortex is replaced by a continuous LEV over the thorax and there is no significant spanwise flow. The structure described by Ellington(1996) and Van den Berg(1997) where the LEV on Manduca is similar to that found on a delta wing. In this model there must be a surface bound focus at the base of each wing and attached flow over the thorax. The flows in (c) differ qualitatively from (a) and (b) in the absence of the linkage between the LEVs via either wing root vortices or a continuation of the LEV across the centreline. Spanwise (axial) flow, if present, is marked by orange arrows in each case. Vertical planes show the simplified flow topology at the centreline and midwing positions.

wasp *Encarsia formosa.* The LEV inflects into tip and root vortices on each wing. The tip vortices connect to form a vortex ring behind the model, and the root vortices also connect so that the wake consists of one continuous vortex loop of complex shape(Figures 9 and 10(a)). The structure described by Luttges[38](1989) with a single LEV extending across the thorax of a hawkmoth and inflecting to form both tip vortices(Figure 10(b)).

This structure implies a free slip critical point (a 3 dimensional focus) over the centerline of the thorax, as described by Srygley and Thomas (2002) for butterflies *Vanessa atalanta*. The structure described by Ellington[40](1996) and Van den Berg[41](1997) where the LEV on *Manduca* is similar to that found on a delta wing. In this model there must be a surface bound focus at the base of each wing and attached flow over the thorax(Figure 10(c)). The flows in (c) differ qualitatively from (a) and (b) in the absence of the linkage between the LEVs *via* either wing root vortices or a continuation of the LEV across the centerline.



[Figure 11] Diagram of the vortex system during the complete wingbeat cycle[42].

A large Leading Edge Vortex(LEV) with strong axial flow is observed during the downstroke (Figure 11). This LEV is still present during supination, but turns into a hook shaped vortex. A small LEV is also detected during the early upstroke, and gradually grows into a large vortex in the latter half of the upstroke. This LEV is still observed closely attached to the wing during the subsequent pronation, where a trailing edge vortex(TEV) and a shear layer vortex(SLV) are also formed, together forming a complicated vortex system.

10. Conclusion

Insects and birds can fly well and they can overcome the disadvantages associated with the range of extremely low Reynolds number. In insects, a Leading Edge Vortex(LEV) can develop along the top of the wing significantly contributing to lift, as their wings continue on their downstroke. LEVs can be quite stable over model insect wings and produce an increase in lift. Birds also employ two different gaits(Vortex ring gait and continuous vortex gait) in flapping flight according to flight speed. Insects and birds also produce vortices in four kinematic portions : upstroke, downstroke, pronation and supination, when the wings rapidly rotate and reverse direction or sweep through the air with high angle of attack(Clap and fling, Delayed Stall, Rotational Circulation and Wake Capture). Birds and insects can modify wing beat amplitude, stroke angle, wing planform area, angle of attack, and to a lesser extent, flapping frequency to optimize the generation of vortices. Birds have various wing planform shape and wingtip shape, and they can control the airstream to increase the total lift coefficient. This study has investigated that the vortices generated due to the flapping motion can generate lift, and vortices are another source of lift force production in flapping wing.

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