

Aerodynamics of Bird and Insect Flight

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Abstract | In this article, the literature on the aerodynamics of bird and insect flight has been reviewed. Emphasis has been laid on the technological requirement of identifying a simple and suitable mechanism, which can be adopted for Micro Air Vehicle (MAV) applications. Large birds use steady aerodynamic principles for their flight, including gliding, soaring and dynamic soaring. Smaller birds and insects, however, use unsteady aerodynamic mechanisms like clap and fling mechanism, delayed stall and wing rotation, wake capturing and asymmetric flapping. The review presents salient features of these mechanisms and highlights the need to consider unsteady mechanisms for micro air vehicle applications. Unsteady mechanisms enable MAVs to hover and perform other maneuvers, which are not possible with fixed-wing, steady-aerodynamic mechanisms. Research is needed to measure all the components of forces and torques produced by a flapping test-rig, while 3-D numerical simulations may identify optimum wing-kinematics and flapping strategies for a given application. These studies will bring out the importance of individual mechanisms in unsteady aerodynamics.

1. Introduction

In this paper, a review of the aerodynamics of bird and insect flight is presented. The presentation here leans towards using unsteady aerodynamics for engineering applications like micro-air vehicles (MAV). Humankind's fascination for flight has been inspired by observing the flight of birds and insects, and this is documented in mythology and history. The Hindu mythology of the *Pushpakavimana*, a flying chariot and the Greek story of an engineer Daedalus, who built wings of wax and feathers to help his son to escape from prison, are two example of legends that amply reflect our interest in flight dating back thousands of years. History tells of Leonardo da Vinci, a French/Italian engineer, who was fascinated by the flight of birds and proposed more than 500 designs for flying machines¹ including the hang-glider and helicopter in the 1480s.^{39a} Eilmer, a 11th century British monk, fascinated by the story of Daedalus, fixed wings to his hands and feet and launched himself from the top of a tower and flew for about 200 m; however,

his flight ended in a fall that broke his legs.⁴ The idea of the ornithopter (a flying machine built based on flapping wings) dates back to pre-historic time, and was successfully demonstrated by Pierre Jullien in 1850s.^{39b} His ornithopter was powered by rubber-bands. Even though the initial engineering approach to flight was centered on flapping wings to generate lift and thrust (ornithopter), designs of modern day efficient flyers are, however, based on steady-aerodynamics as in large birds. The reason for adopting fixed wings (steady aerodynamics) while designing air-craft will become apparent in the following discussion. Humankind's quest for flight was accomplished when the Wright brothers (Orville and Wilbur) demonstrated controlled flight in a heavier-than-air, fixed-wing aircraft in 1903.

Expressions relating wing-beat frequency and the size^{2,32} (characteristic length-*l*) for dynamically similar birds (this is strictly not true because of morphological and physiological differences between various species of birds) can be obtained by

MAV (Micro Air Vehicle): Micro Air Vehicle is an unmanned aircraft, which is smaller than or at least fit into a sphere of 15 cm diameter. This vehicle may be autonomous, that is fly along a pre-programmed path or radio controlled. MAV may generate its thrust and lift by flapping or by rotary wings like a helicopter. This type of vehicles can be used for surveillance, policing, aerial-photography and other applications.

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equating the weight (W) of the flyer to the product of area (A) of the wing and the dynamic pressure ($\sim \rho_a V^2$) developed due to flapping. Where, ρ_a is the density of air and V the characteristic velocity of the wing relative to air. Also, note that $W \propto l^3$, $A \propto l^2$ and $V \propto f l$, thus

$$W \propto V^2 l^2; \therefore f^2 l^4 \propto l^3 \quad \text{or} \quad f = \frac{a}{l^{0.5}}; \quad (1)$$

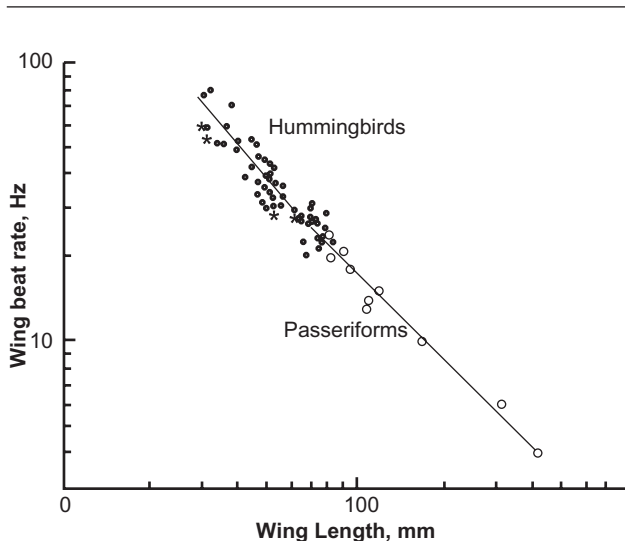
where a is a constant

Table 1 and Figure 1 show the data of flapping frequency for different sizes of insects and birds.⁶ It is evident from this set of data and the expression (1) relating size and frequency, that as the size of the bird/insect (flyer) decreases, its wing-beat frequency has to increase to generate enough lift to keep its weight aloft using smaller wings. While deriving expression for the frequency of flapping (Equation 1), we have assumed that the relative velocity of the wing with respect to air, V , is entirely due to the flapping. However, this is a combination of both forward flight-velocity and wing-tip velocity due to flapping. Thus, for flyers having large wings could generate enough lift just

Table 1: Wing-beat frequencies for insects.

Insect	Frequency (Hz)
Butterflies	4–10
Damselfly	15–20
Dragonfly	25–40
Beetles	40–90
Honeybee	200
Mosquito	450–600
Midges ³⁵	600–1000

Figure 1: Variation in flapping frequency for birds with their wing-size (adopted from).⁶



by moderate, forward velocity without needing to flap their wings. For example, the flight of birds like the eagle and albatross is predominantly gliding, and corresponds to the aerodynamics of fixed wing flight. The distinction between steady and unsteady aerodynamics is determined by the advance ratio, AR , which is the ratio of the forward velocity of the flyer to the wing tip velocity.^{10,14} During hovering flight, when the bird/insect stays at one location (zero forward velocity) by flapping its wings, the advance ratio is zero. While gliding, however, when the wing beat frequency tends to zero and lift is generated solely by the forward speed of the flyer, the advance ratio is infinity. Smaller insects/birds or MAVs have to resort to flapping because if they depend on only forward flight for generating lift, then the required forward velocity will be higher. This makes them ineffective for *surveying* one location or for foraging and other applications.

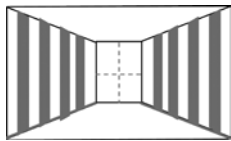
Osborne (1951)²¹ did a systematic study on twenty five insect-species to show that the advance ratio (AR) primarily contributes to enhanced lift and drag compared to steady flight conditions as the advance-ratio is reduced (increased unsteady effects). In this paper, various types of flights are described and unsteady aerodynamic processes that enhance the flight efficiency and/or maneuverability of flight are reviewed along with engineering challenges in adopting these to micro-air vehicle (MAV) applications.

The flight of small birds and insects offers many advantages for engineering applications such as MAVs. In recent times, therefore interest has been generated in the studies of their flight. For applications like surveying hazardous areas, aerial photography and policing, it is convenient to have undetectable, small size MAVs which are maneuverable and can hover over a location. Unlike a large fixed-wing aircraft, a micro-air vehicle which flies by adopting unsteady aerodynamic principles is a better candidate to achieve these objectives. This conclusion is based on the fact that in nature birds and insects do exhibit these qualities in their flight; for example, high maneuverability is displayed by the house fly which can land upside down, or take off sideways. Similarly, the dragonfly and humming bird can hover and fly backwards. Thus at small-scale the necessity of flapping wings for generating lift arises from equation (1), which makes the flight complex, however, provides advantages.

After more than a century of research, the principles of steady aerodynamics for 2-D aerofoil and finite wings applicable to a fixed wing aircraft are reasonably well understood. In contrast, the

Fast-eye: We are more sensitive to notice sudden motion or flickering light compared to static field of view. If, however, the flickering frequency is increased beyond 16–20 Hz, under normal conditions, our eyes we will not notice the flicker. Hence, for human eyes, flicker fusion frequency (FFF) is about 20 Hz. An eye is said to be fast, if the flicker fusion frequency is greater than 60 Hz. Most of the insects have faster-eyes, for example FFF for a house fly is about 270 Hz, dragonfly and blowfly it is up to 300 Hz.

Optic-flow: Suppose an insect is flying in a tunnel, whose vertical walls are marked with strips as shown in the figure below. In the left and

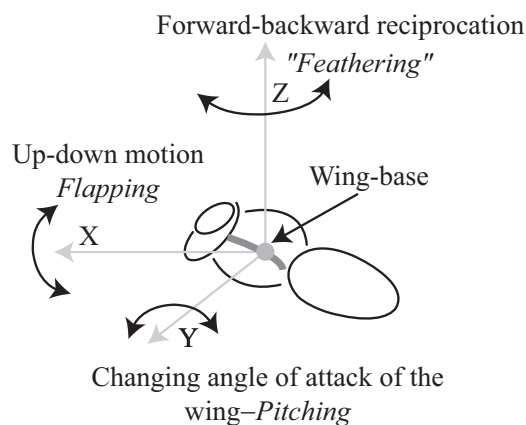


right eyes of the insect, these vertical strips form images. When the insect flies, the images of these strips move in its field of view. Our experience of looking out of the window of a moving bus suggests that images of the objects closer to the bus move faster compared to the images of those objects at farther distance (like a distant hill), in our field of view. Similarly, when the insect is flying in the middle of the tunnel, images in the right and left eyes move at same rate. If the insect is closer to the left wall, then images of strips in the left eye will move faster in comparison to that in the right eye. Thus, insect realizes that it is closer to the left wall, and to avoid collision it will move to the right until the rate of images moving in the right and left eyes are equal. This method of comparing rate of movement of images to know the object's position is known as optic-flow.

engineering principles needed for an optimum design of micro air vehicles, which can use unsteady aerodynamics for their propulsion and lift, have not yet been established. While commenting on the unsteady aerodynamics of bird and insect flight Steven Vogel³⁷ states that the “*difference between a fixed wing and a pair of beating wings is that the wings reciprocate, changing direction and angle of attack during each stroke; and therein is a set of problems for analysis of animal flight even more vexatious than anything so far considered*”. Relatively, the flight of an insect is simpler than that of a bird. A bird in flight not only changes the direction of motion and angle of attack of its wings, it also changes the shape, area and porosity of its wings in a flapping cycle. Thus, insect flight could be the first step in understanding unsteady aerodynamics, though some of the unsteady processes described here are equally applicable to both bird and insect flight. A bird or an insect may use one or a combination of unsteady processes to improve and control its flight.

There are specific features that enable birds and insects to fly effectively in air for foraging, escaping from their predators and for mating. The bones of birds are porous and reduce their weight, and birds and insects have “*faster eyes*”²⁵ which help them to avoid obstacles while flying at high speed. Insects use “*optic flow*”^{34,3} technique, which is based on the differential in the rate of flow of images as perceived by their left and right eyes, to avoid obstacles.

Figure 2: In unsteady-wing motion, wings are moved about the wing base where the wing is attached to the body of an insect. These motions can be resolved about three primary axes- X-along the direction of motion, Y- perpendicular to the X-direction in the horizontal plane and Z- the vertical direction.



The lungs of birds, along with air-sacs, enhance the oxygen supply and so help in maintaining a higher metabolic rate and better thermoregulation. For higher frequencies of flapping, insects have asynchronous-muscles, which set into oscillation when excited.¹¹ Thus an engineer, to achieve sustained & high endurance flight, has to develop many technologies-low weight airframes, micro-power plants, telemetry & controllers and the material used must be multi functional. This review does not address all these issues, and confines itself only to the aerodynamics of flight. A useful starting point on bird flight would be books,^{6,36} a set of papers by Ellington,¹⁰ Shyy et al. (1999)³² and a recent review article by Wu (2011).⁴⁰

2. Types of Flight

There are large diversities in the flight pattern of birds and insects, which reflect their morphological and physiological differences, these are broadly classified here. As said earlier, large flyers generate lift by steady aerodynamics, hardly beating their wings. Under this category, we can distinguish the following types of flight: (a) gliding and (b) soaring.⁶ Similarly, wing motion in unsteady-aerodynamic regimes can be classified into further sub-types. The primary motion of the wing can be resolved along three axes X, Y, and Z as indicated in Figure 2. The forward-backward reciprocating motion is created by rotating the wings at the wing-base about the vertical axis-Z, and is known as “*feathering*”. The rotation of the wing about the X-axis (axis along the direction of flight) produces an up-down motion of the wing which is *flapping*. Finally, the rotation of the wing about the Y-axis causes a change in the angle of attack of the wing and is known as *pitching*. A bird or an insect uses a combination of these three primary motions to achieve a particular wing-kinematics. Continuing with the classification of flight, the types of unsteady wing kinematics are (c) Weis-Fogh or clap and fling mechanism^{18,38} first reported in the insect *Encarsia-formosa*, (d) delayed stall along with wing rotation (Maresca et al., 1979¹⁷ and Ellington, 1984)¹⁰ which results in enhanced lift at high angles of attack and generates lift at the ends of the wing-strokes (Ellington, 1984¹⁰ and Dickinson et al., 1999),⁸ (e) wake capturing (Dickinson et al., 1999)⁸ for maneuvering and (g) asymmetries in flapping. Each of these types will be described in detail in the following section.

(a) Gliding: Large birds like eagles, marsh-harriers, gannets, vultures, bats and frigates and some butterflies exhibit this type of flight. Gliding is the action of flying or moving through the air⁹ without the flapping of wings, but, with active

control of aerodynamic forces (lift and drag). It is a special case of horizontal flight powered by gravity.⁶ The efficiency of gliding is indicated by the glide-ratio, which is the horizontal distance covered by the glider for a unit drop in height. Figure 3 shows the glide-ratios for different birds.⁶ A glide-ratio below one is not gliding, but is termed as controlled parachuting (for example in arboreal ants).⁹ Birds having a large wing-span are good gliders, albatrosses being the best. Birds having lower glide-ratios tend to beat their wings at higher frequencies, thus highlight the need for unsteady aerodynamics to keep up their flight

(for example, sparrows and pigeons). Gliding birds first gain height by flapping or climbing and then switch or jump to gliding. Among insects moth, cockroaches, and commander and monarch butterflies are examples of gliders. Butterflies glide by opening their wings in a “V” shape and control the rate of descent by varying the opening-angle.

The weight of a bird or an insect which glides with a steady velocity V , along an inclined path making an angle α with the horizontal can be resolved into two components, one along the glide path and the other perpendicular to the glide-path as shown in Figure 4. The lift force (L) generated balances the

Figure 3: Glide ratio for different birds, adopted from.⁶

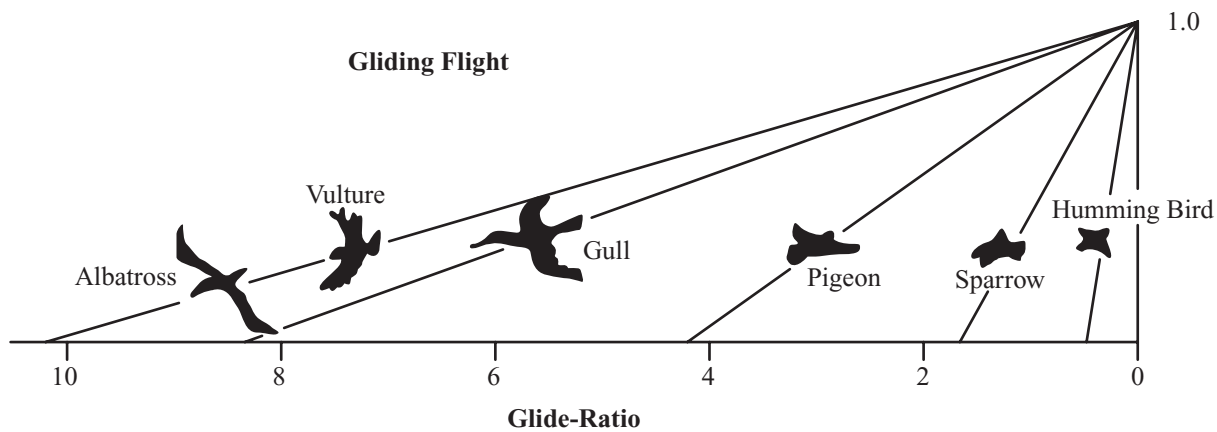
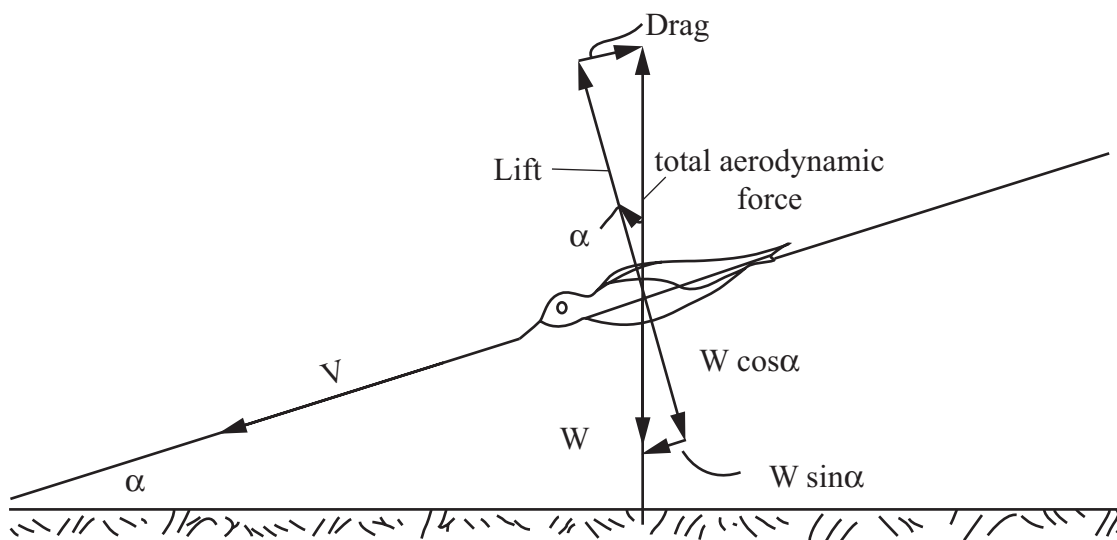


Figure 4: Forces on a gliding bird.⁶



weight component $W \cos(\alpha)$ and the drag (D) is balanced by $W \sin(\alpha)$. If ρ is the density of the air, S is the surface area of the wing and C_L and C_D are the lift and drag coefficients respectively, then

$$\begin{aligned} L &= \frac{1}{2} \rho V^2 S C_L = W \cos(\alpha) \quad \text{and} \\ D &= \frac{1}{2} \rho V^2 S C_D = W \sin(\alpha) \quad (2) \\ V &= \left[\frac{2 C_L \cos(\alpha) W}{\rho S} \right]^{1/2} \end{aligned}$$

The gliding velocity, V , is proportional to the square root of wing loading (W/S). In effect, a heavier bird having smaller wings would have a higher gliding velocity. This also relates to the paradox of the bumblebee's flight; if one goes by the observed flight velocity of the bumblebee and corresponding wing loading, it should not be able to fly. However, the flapping of the wings increases relative velocities, and other unsteady aerodynamic effects (discussed later) help the bumblebee to generate enough lift to stay in the air. The gliding angle, α , of the bird is determined by the ratio of drag and lift coefficients as follows,

$$\alpha = \tan^{-1} \left(\frac{C_D}{C_L} \right)$$

(b) Soaring: Soaring is a method of flight in which a bird would obtain lift from the upward air current generated from hot spots or an orographic

condition. Rayleigh²⁴ gave a mechanistic explanation of soaring. Figure 5 shows two conditions under which soaring is used by birds. Examples of birds using rising thermal currents for soaring include vultures and hawks. The main difference between gliding and soaring is that birds gain altitude rather than lose it as in the case of gliding. Birds, while foraging using soaring and glide from one thermal to another. After sunrise, birds wait a few hours for thermals to develop and then they start their flight. They circle around the rising column of hot air and gain altitude, while looking for their food on the ground. After reaching the height of the thermal or for moving to a different location, they glide down covering a horizontal distance until they catch another rising column of air in the vicinity. The climbing rates observed for soaring raptors (vultures, eagles and hawks) are about 1.5–2 m/s and chiefly depend on the strength of the thermal.³³ The inter-thermal gliding speed is about 50–60 km/hr.³³ In orographic assisted soaring or slope-soaring an upward wind is generated by blocking effect of hillocks or ridges and the birds ride on this upward-draft to support their weight along the ridge.

In another related method called dynamic-soaring (refer Figure 6), birds extract energy from the wind gradient; they exploit the fact that the velocity at the surface (on water or on ground) is lower than that at higher altitude. A bird, at location A, with its kinetic energy (velocity), orients itself against the wind and gains altitude and reaches the point B where it has high potential energy. Then it

Figure 5: Soaring of bird using (a) hot-air currents and (b) upward wind of orographic origin.

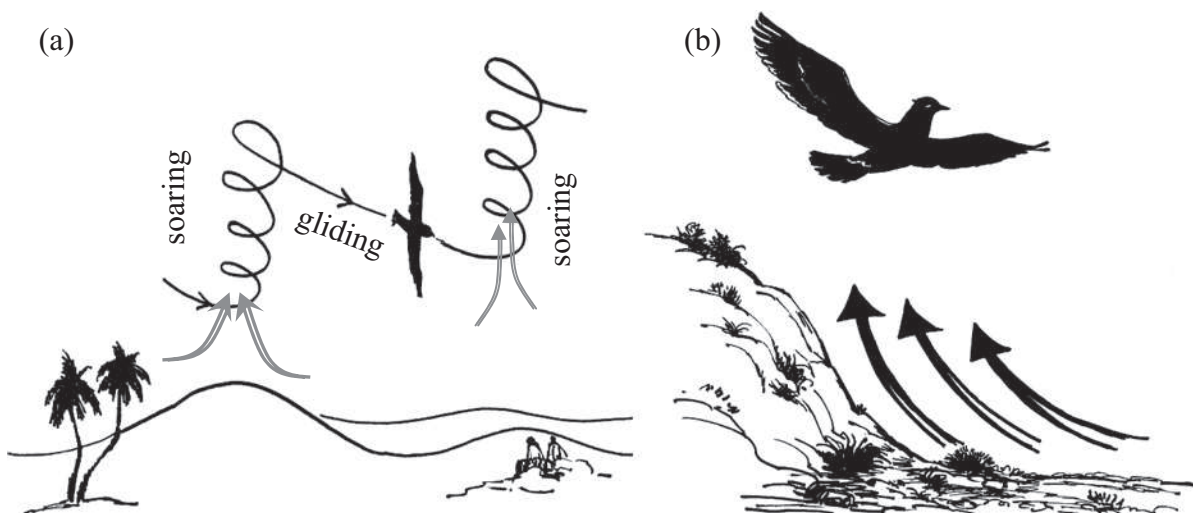
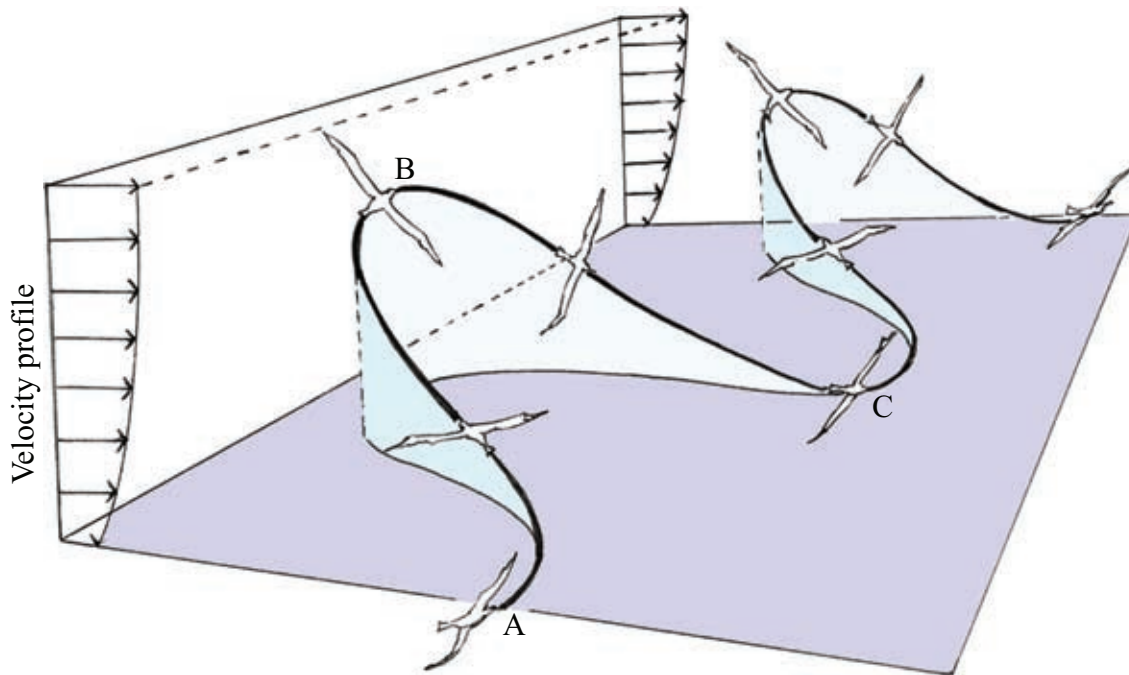


Figure 6: Schematic diagram indicating dynamic soaring. At point A, bird is at the lowest position and has high kinetic energy (high velocity), at point-B it has gained height by flying against the wind and it glides down towards point C while taking advantage of tail-wind and gain velocity.

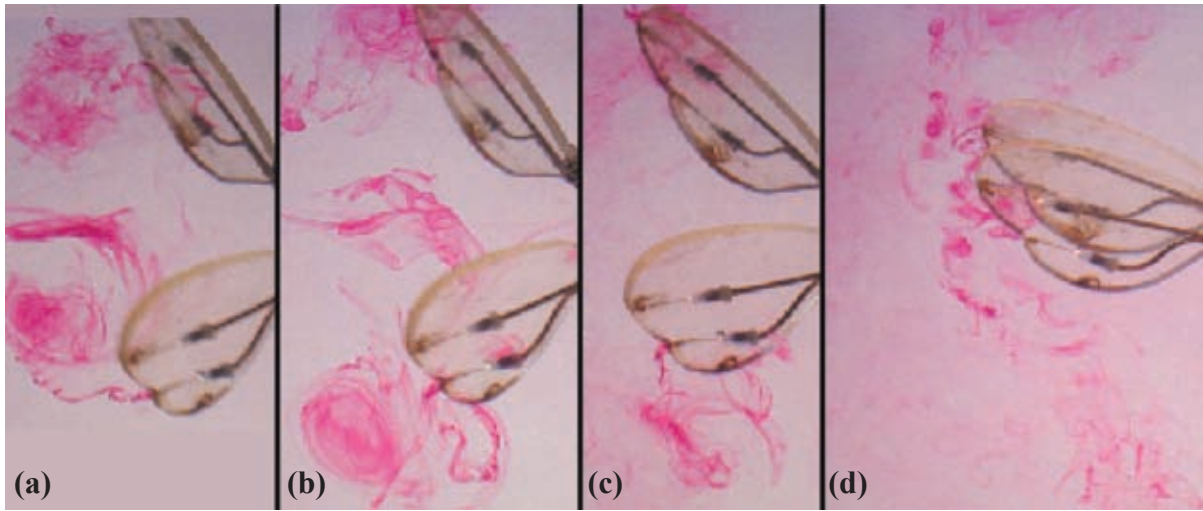


turns towards the wind direction and glides down towards point C. While gliding down, it is helped by the high tail wind and gains kinetic energy both by the loss of potential energy and push of the tail-wind which more than compensate for the drag force. Around point C, which is close to the surface, it covers the horizontal distance with little wind resistance. Thus the bird extracts kinetic energy from the wind at high altitude and uses it to scavenge at the surface. Over the sea surface, when the wind speed is about 15 m/s, albatrosses are observed to “pull-up”, and climb to an altitude of 15–20 m from the sea surface²² by flying against the wind. They continue to fly by this method without beating their wings for a long duration as long as a wind-gradient is present. This is similar to the “tacking” technique employed by sailing boats to move in a direction against the wind by sailing in a zigzag manner.

(c) Weis-Fogh mechanism: The two previous methods of generating lift are based on steady-aerodynamics; we shall now look into unsteady mechanisms. Clap and fling or the Weis-Fogh mechanism is described in references [15, 18 and 38]. The Weis-Fogh mechanism is a simple wing kinematics, reported by Weis-Fogh to describe the

flight of a wasp (*Encarsia formosa*). Experimental flow visualization depicting the flow is shown in Figure 7. When the closed wings on the upper side of the wasp are flung apart, air rushes into the open space (Figure 7a and b) and as a reaction, the wasp experiences an upward lift. The wings continue to move down as they continue to push the air in the downward direction (Figure 7c). At the end of the downward motion, the wings are rotated and starts closing (clapping phase). First, the leading edge of the wings are joined and then they progressively close towards the trailing edge. During the closing of wings air is therefore squeezed backwards and so creates a forward thrust (Figure 7d). This type of flight is adopted by tiny insects like wasps and fruit flies and large insects like butterflies, damselflies and moths.¹⁶ Marden¹⁶ also shows that maximum lift is generated during take-off for insects adopting the clap and fling mechanism. The advantage of this mechanism is that the lift generation is instantaneous; when a butterfly opens its wings (flings them apart) it will immediately be airborne. However, the lift generated is highly unsteady and results in an erratic flight path as observed in many butterflies. Lighthill¹⁵ has derived an analytic expression for the dependence of lift force on the included angle of a

Figure 7: A sequence of photos showing the development of the flow field in the clap and fling motion of the wings.⁵ The wings used are scaled copy of a butterfly wings and visualization is by dye-injection at the wing-tip.



pair of 2-D wings performing a “fling” motion.¹⁵ Maxworthy¹⁸ later conducted experiments on the flapping mechanical model, and found that the actual lift produced is significantly more than that predicted by the inviscid theory of Lighthill. A schematic diagram in Figure 8, shows various stages in the clap and fling motion of a butterfly wing. Kinematically, clap and fling motion is simple and generates instantaneous lift during the opening of the wings (fling); thus, a butterfly can fly immediately on opening its wings.

(d) Delayed stall due to unsteady motion and wing rotation: For an airfoil in motion with constant velocity (U) and at an angle of attack (α) steady-circulation ($\Gamma_s = \pi CU\alpha$) around the wing leads to the generation of lift ($L_s = \rho U \Gamma_s$ per unit length of the airfoil), where, ρ is the density of the air, and C is the chord-length. The angle of attack α takes care of the effect of the profile of the airfoil. When the angle of attack of the airfoil is large, the flow over the airfoil surface separates and stall occurs and the airfoil loses its lift. Let us say the angle-of-attack at which separation occurs for a wing under steady motion, is α_s . However, if the airfoil is set into motion abruptly or its angle of attack is increased by rotating the airfoil ($\omega = d\alpha/dt$), the stalling angle in both cases is increased beyond α_s , as it takes some time for the flow to develop and separation to occur. During this period the airfoil can travel several chord lengths at larger angles of attack ($\alpha > \alpha_s$) before stall begins. Due to these unsteady effects and higher angles of attack in this

period, large transient circulation and hence lift can be generated.

A delay in the onset of stall due to the abrupt translation of the wing is known as the Wagner-effect¹⁰ and the enhanced circulation and delayed stall due to the rotation of the wing ($\omega = d\alpha/dt$) is known as the Kramer-effect.¹⁰ In the quasi-steady theory the total circulation (Γ_Q) generated by a wing is calculated as the sum of that due to wing translation (Γ_T) and wing rotation (Γ_R) about a point at the distance, S_o , from the leading edge of the wing. That is,

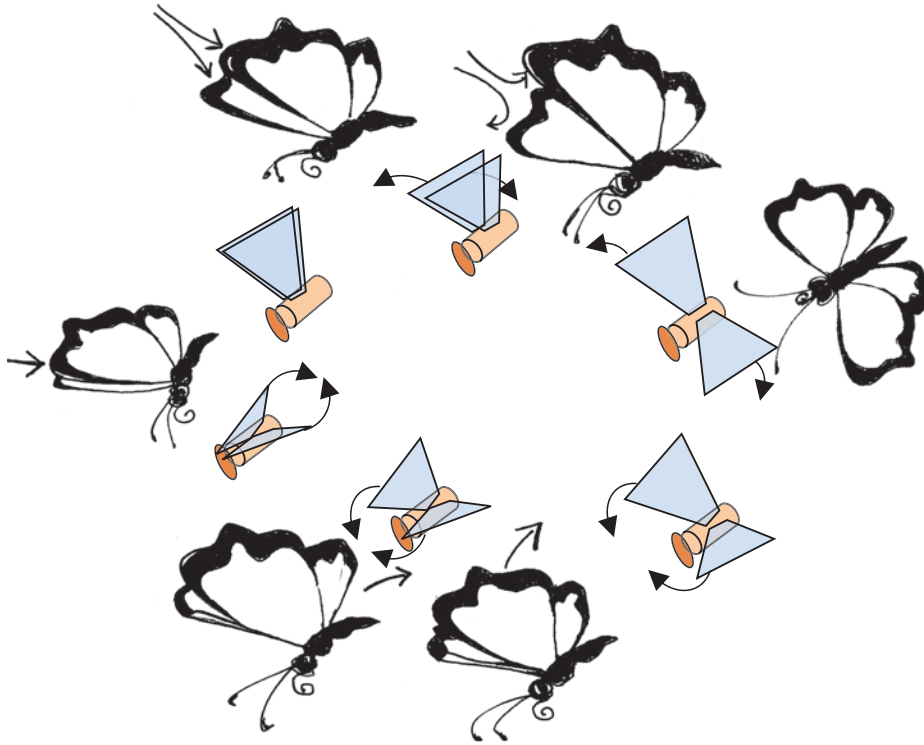
$$\Gamma_Q = \Gamma_T + \Gamma_R = \pi CU\alpha + \pi\omega C^2 \left(\frac{3}{4} - \hat{S} \right) \quad (3)$$

$$\approx \pi CU \left[\alpha + \frac{\omega C}{U} \left(\frac{3}{4} - \hat{S} \right) \right]$$

Where $\Gamma_R = \pi\omega C^2 (\frac{3}{4} - \hat{S})$, is the circulation developed due to the wing rotation and \hat{S} is the non dimensional distance from the leading edge of the wing to the axis of rotation on the wing.

In Figure 9a, the graph indicates the variation of circulation and lift normalized by that predicted by the quasi-steady expression given in Equation 3 with non-dimensional translation (X/C). In plot Figure 9b, instantaneous circulation is compared to the maximum circulation generated during a steady-stall condition. It is evident from the plots that instantaneous circulation during unsteady aerodynamics is larger than that produced during a steady-condition when the wing translation is larger than about 1.5 times the chord length.

Figure 8: Schematic diagram indicating clap and fling mechanism in a butterfly. During the fling (opening of wings) air rush into the space between the wings generating lift. Reversing the direction of motion for closing (clap-phase), wings at the base is rotated so as to make leading edge to close first, thus air in gap is expelled backwards creating thrust.



Another notable feature is that normalized lift starts from the value 0.5 and slowly approaches one as the wing displacement tends towards five chord lengths. The initial lift is due to the rotation of the wing (through Γ_R). The enhanced circulation must eventually be lost as the flow separates from the upper surface & a steady case is realized. If the insect completes its stroke before the onset of stall, it can enjoy a higher lift than the steady state value. Thus insects exploit unsteady aerodynamic principles of delay in the onset of stall and enhancement of lift through Wagner and Kramer effects. To put it more simply, insects maintain lift even when they beat their wings with high angles of attack and generate more lift than the steady state values by the rotation of wings and transient effects. When an insect stops its wing at the end of a stroke ($U \rightarrow 0$), to reverse its motion, lift is wholly generated due to the rotation of the wing. Note that in equation (3), the term $\omega C/U$ captures the unsteady effects. Enhanced lift was observed for $\omega C/U$ values greater than 0.003, which was more than twenty times the maximum steady-stall value.^{13,10}

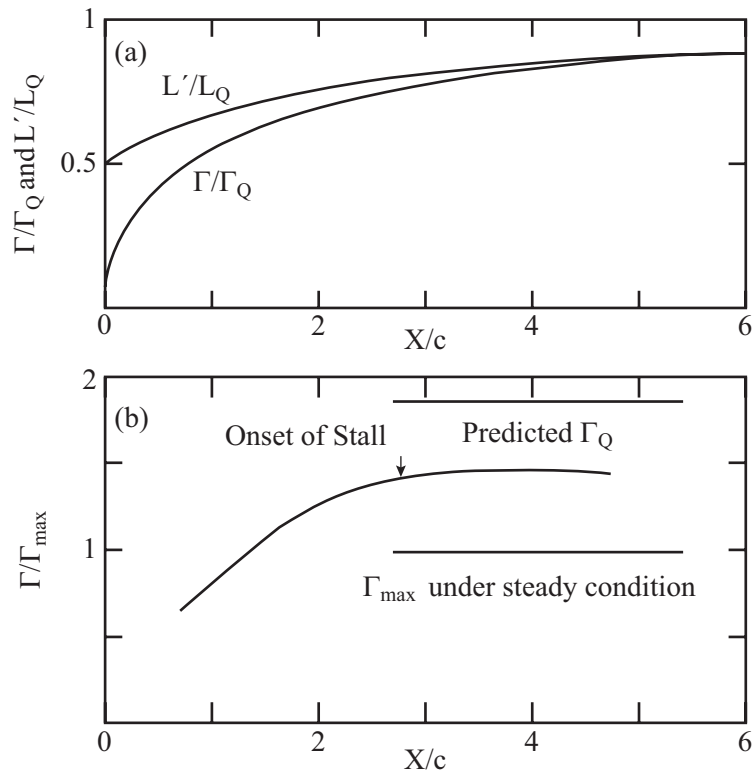
(e) Wake capturing: Wake interaction for bird or insect flight can happen in two ways. When birds fly

in formation or in a swarm, the flight of individual birds or insects is affected by the wake of others in the formation or swarm and this can affect the control of insect flight. Secondly, the wing of an insect or a bird can interact with the wake of its previous stroke and is therefore exploited in maneuvering.⁸ This effect can help them in producing higher lift or in other maneuvers like taking a turn or braking.

(f) Asymmetric flapping and wing flexibility: Birds and insects flap and reciprocate their wings in a cyclic manner. However, the desired effect of the kinematics is to produce an upward force to balance the weight and thrust to compensate for the drag force. Thus, the forces generated by the flyer through its wing kinematics and interaction between the wing and the flow have to break up-down symmetry (to produce net lift force) and front-back symmetry (for net thrust). In this section, we discuss four symmetry-breaking mechanisms, which are exploited by insects and birds in their flight.

It has been found by Childress and his co-workers^{19,20} that the vertical flapping of a wing at a Reynolds number above a critical value results in the breaking of fore-aft symmetry and pure vertical

Figure 9: Variation of circulation and lift with wing displacement, adopted from,¹⁰ X is the translation-distance, C is the chord-length of the wing.



oscillations that will result in the forward motion of the wing. Their experimental setup consists of a circular tank carrying working fluid. At its center, a vertical rod supports a horizontal plate of width C which can oscillate in the vertical direction. The plate is free to rotate in the horizontal plane about the vertical axis. If the frequency of oscillation is f , amplitude is a and the fluid viscosity in the tank is ν , then the Reynolds number based on the frequency of oscillation and the amplitude is $Re_f = a f c / \nu$. When the value of Re_f exceeds 250–400, the plate starts to rotate spontaneously about the vertical axis, with a hysteresis-loop covering the Re_f range. Note that in this case symmetry breaking is spontaneous, and results from the non-linear interaction of wake and the body above a critical value of Re_f , even though the wing kinematics is symmetrical.

We^{5,7,28–31} have identified other asymmetric-flapping mechanisms that could help in generating lift-force by breaking up-down symmetry in flapping flight. These sets of studies are based on flow-visualization experiments using a flapping test rig and two-dimensional simulations based on the discrete-vortex method. The first mechanism is based on wing-kinematics in which the duration for the down stroke (t_D) is shorter than that for the upstroke (t_U). The ratio of the down-stroke duration to the upstroke is known as the asymmetry ratio ($A = t_D/t_U$). When A is equal to one, it is termed as symmetric flapping. In Figure 10, flow fields

Figure 10: Streak photograph of the flow field developed in (a) symmetric flapping and (b) asymmetric flapping.^{28–31} In Symmetric flapping, flow field 4-jets, two moving upwards and two moving downwards, mean-displacement of fluid over a cycle is neither in the upward or the downward direction. During asymmetric flapping fluid is sucked from the sides and pushed downwards through 2-jets, thus producing a net upwards force.

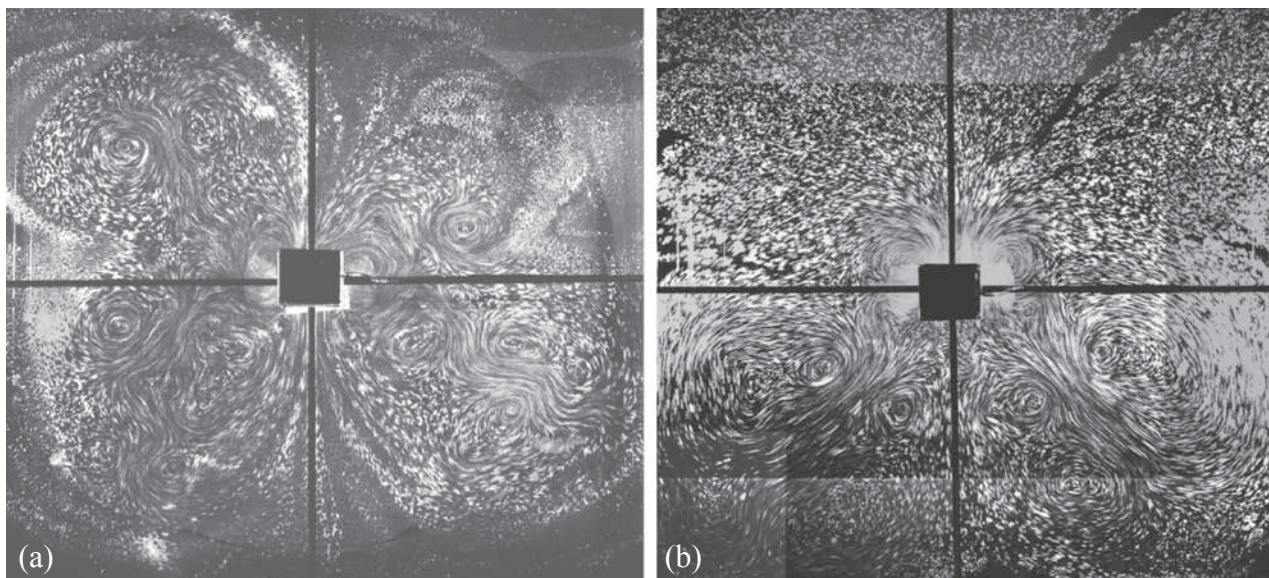


Figure 11: Plot depicting region in which asymmetric flapping can generate lift as a function of flapping frequency based on the duration for down stroke ($=1/2t_d$).²⁸⁻³¹

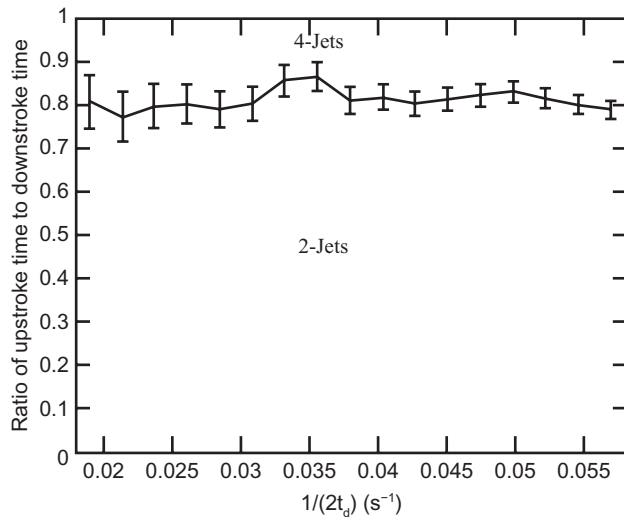
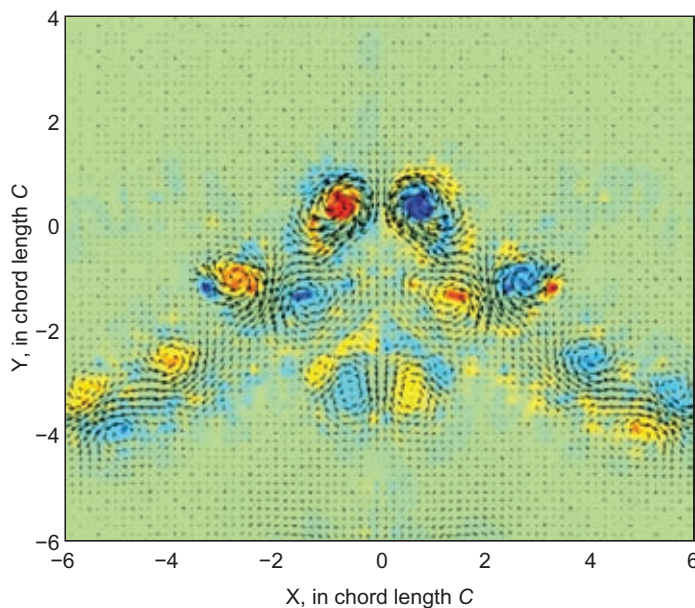


Figure 12: A flow field developed in asymmetric flapping computed by the 2-D, discrete-vortex method; colour represents vorticity field and vectors represent local velocities.²⁸⁻³¹



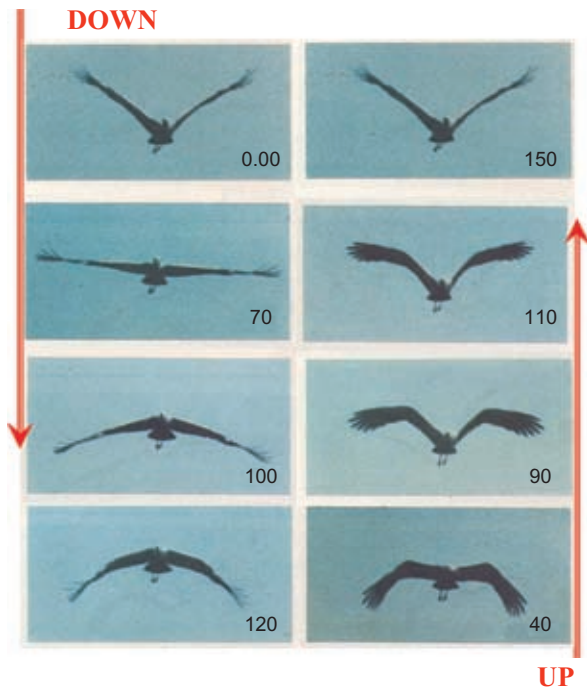
produced by two types of wing kinematics are shown; the flow fields are captured by streak-photography. Figure 10a indicates that for symmetric flapping (the asymmetry-ratio is one or $t_d = t_u$) and Figure 10b shows the flow field developed during asymmetric

flapping. In the case of symmetric flapping ($A = 1$), the flow field indicates the formation of four jets, two going upward and two going downward. Thus over the entire cycle, fluid is neither pushed preferentially downwards or upwards, and hence the net-force generated is zero. However, in the case of asymmetric flapping ($A < 0.7$), the flow field indicates that fluid is sucked from the sides and pushed down in the form of two jets moving in the downward direction. The switch of the flow field from a four-jet configuration to a two-jet configuration was monitored for various down-stroke periods (Figure 11) and occurs when the asymmetry ratio falls below 0.7 (that is $A \leq 0.7$).²⁸⁻³¹

Two-dimensional, discrete-vortex method based simulations also capture this bifurcation in the flow field from two to four jet configurations. In Figure 12, a flow field developed in asymmetric flapping with two, downward moving jets is shown. In nature also, asymmetric flapping seems to be in operation for lift generation. It has been reported in insect diptera¹² and in the bird Painted-stork⁶ that the duration for the down-stroke is shorter than that for the upstroke, and the asymmetry ratio is about 0.7. In the context of aquatic locomotion, Shinde and Arakeri,^{26,27} show that a flexible-flap (fish-tail) can make the wake two-dimensional and produce extra thrust. Their flow visualization indicates small vortical structures carrying energy from the flapper; however, while surveying wake using PIV, one may miss these fine structures depending on the spatial-resolution of PIV. In their experiments, Shinde and Arakeri^{26,27} observe a single jet emanating from the flapper; even when the flapping is symmetric ($A = 1$), the difference between these two observations may be due to the amplitude of flapping. It has also to be noted that a pitching airfoils in an uniform flow can produce different types of wakes (undulating wake, double-wake, Von-Karman vortex-street and reverse VK vortex-street) depending on reduced flapping frequency and non-dimensional flapping amplitude.²³

Other types of asymmetry that can be incorporated into the wings are (a) controlled wing flexibility,^{7,31} and (b) flapping with the mean position of wings below the horizontal plane.^{7,31} If one incorporates controlled wing-flexibility so as to mimic the bird's wing motion as shown in Figure 13, the wing in the down-stroke comes down flat and increases the amount of air pushed down. Hence, there is an upward reaction force. During the upstroke, however, the wing is bent so that resistance to its upward motion is reduced. Simulations based on this type of directional wing flexibility indicate that the lift produced is almost

Figure 13: The wing motion of a Painted-stork depicting down-stroke with flat-wing coming down whereas during the upstroke the wings are bent to reduce resistance to upward motion, adopted from.⁶



doubled.^{7,31} If the variation of wing flexibility is introduced along the chord, it could generate forward thrust. The flapping of wings below the horizontal plane^{7,31} makes the downward jets move down vertically and this again increases the magnitude of the lift force (see Figure 14). In both cases (increasing flexibility or increasing the inclination of the wing's mean position), if the flow produced by opposite side wings starts interacting at the end of down-stroke, advantage of enhancing lift rapidly reduced.

The variation of lift force produced as a function of the asymmetry ratio, A , (Figure 15) indicates that lift-force has a maximum for the optimum value of A which is about 0.7. This optimum is more pronounced for cases with higher frequencies of flapping.^{7,31} A design chart indicating the lift force produced as a function of flapping frequency and size of the wing of the type shown in Figure 16, is useful in developing a configuration of MAV for a particular application. However, note that these values are based on two dimensional simulations and a confirmation based either on three dimensional simulations or experimental measurement of forces using a flapping test rig, is needed.

Figure 14: Effect of inclination of the mean-position of wings to the horizontal plane on the flow field. 2-D simulation for rigid wings flapping with an amplitude of 80° , $t_D = 0.013s$ and $t_U = 0.026s$ ($A = t_D/t_U = 0.5$). (a) The mean position of the wings coincides with the horizontal plane (0° inclination) and (b) the mean position of the wings is 20° below the horizontal plane (-20° inclination). The colour represents the vorticity field and vectors represent local velocities, note that the jets have moved towards the vertical axis as the inclination is increased.^{7,31}

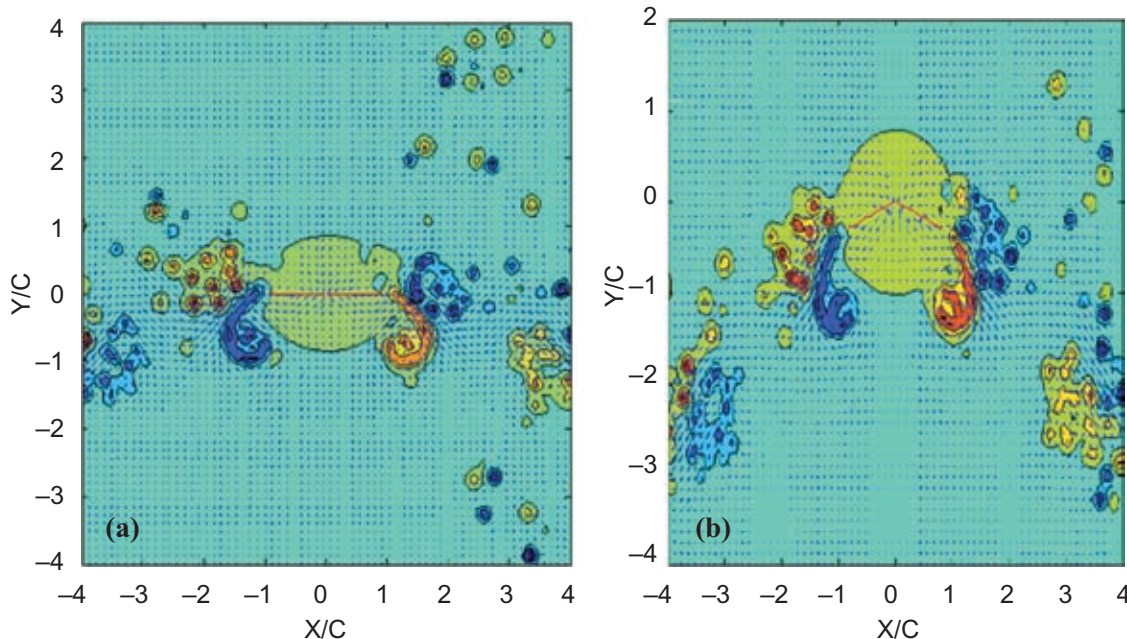


Figure 15: Identification of optimum asymmetry ratio (A) for different down-stroke flapping frequencies. Simulations for rigid wings, flapping with an amplitude of 80° , and an inclination of -20° to the horizontal.^{7,31}

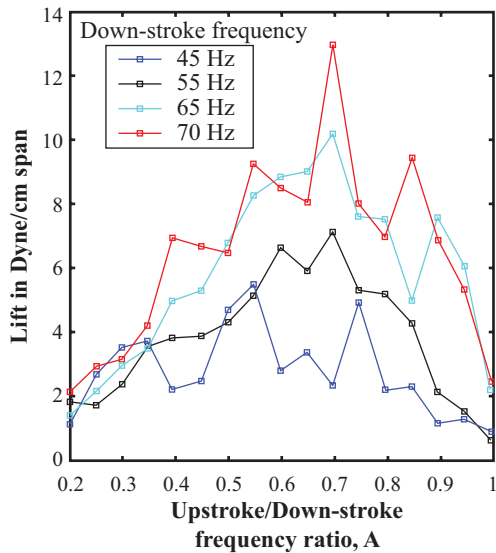
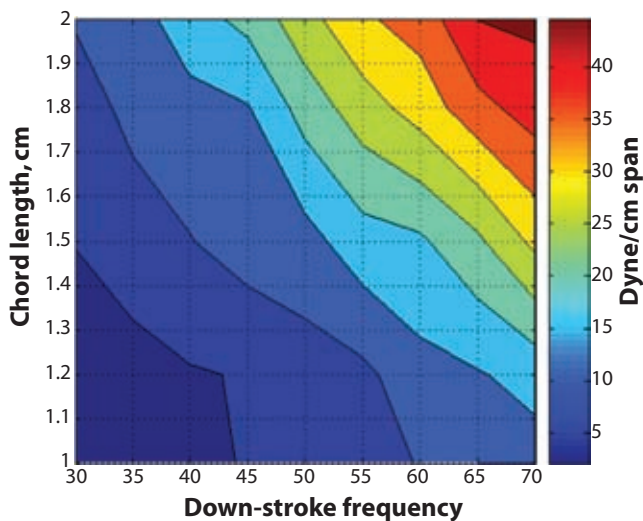


Figure 16: Contour plot indicating optimum lift generated for a given chord length of the wing, flapping at different down-stroke frequencies with rigid wings, flapping amplitude of 80° , and an inclination of -20° to the horizontal.^{7,31}



3. Conclusions

In this article we have reviewed various aerodynamic principles used by birds and insects with the intention of adopting them in Micro Air Vehicles. One of the arguments for adopting a flapping method for MAV is its efficiency; however, this

point has never been demonstrated conclusively. For achieving slow forward flight/hovering, with smaller wings, one has to either adopt flapping flight or the helicopter type of lift-production. Here again, it is not apparent which is more suitable. Many researchers have developed wing kinematics, which exactly replicates the wing kinematics of a bird or an insect. This approach may not be required for MAV applications. An insect's wing kinematics is restricted by the physiological constraints, whereas an engineering device may adopt only the essential feature of the unsteady aerodynamics without replicating complete wing-kinematics of that insect. Various factors like endurance, stealth by blending into natural background, and maneuverability may finally determine the adoption of a particular mechanism to MAV application.

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