Recent evolution of low reynolds number flyers: Paving way for Micro Air Vehicles (MAV)

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Abstract. For a number of manmade and natural flyers the aerodynamics of low Reynolds number plays a crucial role. Active study of birds and insects is growing rapidly for development of Micro Air Vehicles (MAVs). MAVs are capable of performing tasks like surveillance, environmental monitoring and threat assessment in hostile environment. When compared to general civilian aircrafts MAVs fly at low Reynolds number regime of $10^5$ or lower. A considerable change of aerodynamic characteristics is seen between aircrafts that operate in low and high Reynolds number regimes. Low Reynolds number flyers are sensitive to wing gust and deformation because of being lightweight and operating at low speeds. The birds have nature’s finest locomotion system when it comes to maneuvering effectively through space. This review paper will assist further studies in the field of low Reynolds number flyers that can be used for future development on MAVs. A holistic review of past two decades of research work and studies done on low Reynolds number flyers has been presented in this paper. The Theoretical, Experimental and Numerical techniques followed by researchers have been highlighted so that the study on biological and manmade flyers can be systematically presented. It was found that researchers preferred Numerical and Experimental techniques while conducting aerodynamic analysis of low Reynolds number flyers. An attempt has been made in this paper to fill the research gap that is there in mimicking the flight of animals and thus developing man-made systems having higher efficiency.

1. Introduction

Biological flyers have been of interest to scientists and researchers for a long time because of the excellent flying capabilities possessed by them. Birds, bats and insects are capable of carrying out manoeuvring flight with extreme precision because of a number of design features that these have adapted to over millions of years of evolutionary process. Out of the 13000 species of birds and mammals nearly 10000 species can successfully fly. Out of those 10,000 flying species, 9000 are of birds and 1000 of bats. Man-made flyers like SR-71 have been able to attain speeds of about 32 body lengths per second. But a simple natural flyer like a pigeon travels at about 75 body lengths per second. It can be said that birds fly professionally but humans fly for commercial reasons.

This paper reviews various literature on studies that have been conducted to understand and evaluate the aerodynamics of biological flyers. An overview of different low Reynolds number flyers has been presented and their flight characteristics along with scaling laws have been discussed. The
developmental work on new technologies like Micro Air Vehicles (MAVs) and morphing structures has also been reviewed. The development of MAVs depends primarily on the study of aerodynamics of avian flight because MAVs cannot be developed by solely using classical aerodynamic theories. Initially the MAVs were defined as having a maximum size of 15 cm with a flight speed of around 10 m/s. Just like biological flyers MAVs operate at low Reynolds number regime of $10^5$ or lower. The development of MAVs depends on a number of factors like availability of materials, miniaturisation of power systems, communication system development etc. Different groups of MAVs have been developed that have fixed, rotary and flapping wings based on biological inspiration from flapping wing insect like dragonflies. The hovering technology has taken inspiration from hummingbirds which can hover effortlessly. The bat’s wing inspired researchers for development of actively morphing technologies because wings of bats have live tissue which allows them to change the wing properties like camber during flight itself. Development of flapping wing involves great challenges because of the structural movement and unsteady aerodynamics involved with it. The aerodynamics of fixed wing conventional airplanes is far simpler than that of flapping wings. The scaling laws show that with reduction in body size of flyers the flapping speed increases and a reduced wing loading is experienced. Birds, bats and insects employ different flapping styles in various flight modes like forward flight, hovering, reverse flight etc. As the flyer operates in low Reynolds number regime the wing of the flyer generates lower lift-to-drag ratio. Flapping wings help overcome several problems of low Reynolds number flight.

2. LITERATURE SURVEY

The ability of birds to fly has made them one of the most studied animals by biologists and researchers. Because of the capability to fly birds are able to find the most suitable climate and seasons for their reproduction and survival. In the search for appropriate climate for breeding birds migrate to distances more than 10,000 km by flying non-stop. The ability of birds to fly non-stop for such long distances surpasses the range and endurance of any man-made flying vehicle. Anders Hedenstrom [1] has aimed at reviewing the aerodynamic approach taken by researchers in order to study bird flight. With modifications in the aerodynamic theory of aircrafts, the study of bird flights has been possible so that obstacles related to animal flights can be addressed. With proper application of theory of flight to birds it has been possible for humans to calculate data related to bird flight like the range, moderate speed and the migration strategies adopted by birds. Without using aerodynamic theory it becomes impossible for ecologists to analyse the flapping flight of birds due to the physiological complications involved. For modelling bird flight aerodynamics there exists two major approaches as shown in figure 1. First method involves the calculation of local force that acts on a wing-strip and thus integrating the result obtained over the whole wingspan. The other approach is called ‘Vortex Wake’ method. Flapping wings tend to disturb the surrounding air thus Impulse of the wake and momentum change have an impact on the aerodynamic force, is made use of by the vortex wake method. Thus lift and drag can be calculated by using topology and kinetic energy stored in the wake of flying bird.

![Figure 1. To study aerodynamic force on birds two approaches were taken. (a) Here aerodynamic forces were calculated for thin wing sections. (b) Here aerodynamic force calculation was done using wake properties [1].](image-url)
For small birds having rounded and low aspect ratio wings, the most common form of flight is intermittent bounds flight. Intermittent flight involves phases of flapping mixed with flexed-wing bounds. In flexed-wing bounds the wings are kept motionless and flexed against the body. But small birds having pointed high aspect ratio wings carry out intermittent bounds along with glides whenever required. During glides the wings are extended. It has been observed that as the mass of birds increases the use of intermittent bounds decreases. In general for small birds, flap-bounding is a commonly used style. In flap-bounding flapping phases are in alternate with flexed-wing bounds. The reason for flap-bounding to be a common flight style is the body lift. For separately studying the importance of body and tail in lift and drag Bret W. Tobalske et al [2] made use of Particle Image Velocimetry (PIV). The bird taken into consideration was zebra finch and its wake properties were studied using PIV experiment when flying at 6-10 m/s. The air velocity was kept between 2-12 m/s when specimens were used. The body angle of specimens varied from -15 to 50 degrees. For conducting the experiment five live zebra finch and four specimens were used. The whole set of experiments was performed in a variable speed wind tunnel.

Balajee Ramakrishnananda et al [3] aims at applying the principles of aerodynamics for conducting physical animation of bird flight. For animating the forward flight of birds a physical model has been described and an initial condition was taken. Initially only that motion was considered in which the coordination between the two wings of a bird was symmetric. It was assumed that no sideward component of the wind is coming into play. Balajee Ramakrishnananda et al developed three approaches for doing the physical animation. After changing various geometric parameters of the wing and varying the airfoil cross section, the wing of a bird was generated. Various motions of the wing were taken as functions of time. Aerodynamic and gravitational force distribution acting on the wings were used in order to predict the bird’s trajectory during flight. The three motions that birds perform are flapping, twisting motion and lead-lag. Newton’s laws of motions were applicable for the basic equations of bird flight also. Now for decreasing the time taken for computation two assumptions were made. One is that the induced velocity was neglected and the other is that quasisteady assumption was taken while analysing the flow. In order to verify the capability and working of the system animation sequences were made for different phases of flight.

Bats are flying animals having unique capabilities that distinguish them greatly from the other flying animals like the birds and insects. Bat wings are compliant and they have an echolocation sensory system that gives them several advantages over the birds and insects. The aerodynamics of a flying bat is greatly influenced by the echolocation capability that allows the bat to fly in during night also. The oldest bat fossil found dates 55 million years back. Since that time the body structure of bats have diversified to adapt to different ecological conditions of the surroundings. The bat wings have various sizes and vary from short to broad sizes. Short wings allow bats to fly in small places while the species that live in open regions have broad wings. The bat airframe is different from other flying species of animals. The natural structure of the wing surface is unique in bats. In other flying animals like birds the wing is made up of dead skin thus limiting the ability of the birds to control the shape of the wing. On the other hand the bat wings are made up of live skin that stretches from the elongated arms. The skin in a bat’s wing is 4-10 times thinner compared to wings of other animals and also the wing bones are light weight. The overall weight of a bat wing is considerably less than expected. The skin on the wing of bats has several properties like being made up of elastic fibers, having sensors and better compliance. The camber of the bats wings is controlled by the intrinsic muscles which is not joined to any of the bones. Anders Hedenstrom et al[4] have reviewed that the intrinsic muscles are active during certain phases of flight which improves the aerodynamic performance of the bats. Interestingly the efforts of humans to create morphing aircraft structures have not yielded any fruitful results but bats have been using morphing technology for a long time. Bats have the morphing ability because of the fact that the wings are stretched by the fingers thus giving them the ability to vary the shape of wing. Because of the fingers the wing can be turned to various degrees and also the wing area
can be changes thus taking the shape whichever best suites the flight conditions. It has been found by researchers that for slow flights where the lift requirement is high the wings have larger surface area and higher camber. The mechanism that gives the wing stiff leading edges is called Norberg mechanism.

Today one of the major challenges in aviation sector is to reduce the fuel consumption done by aircrafts because the fossil fuel reserves are depleting very rapidly. The fuel consumption can be significantly reduced by reducing the drag during flight. For reducing the drag a number of approaches have been proposed by researchers for a long time as the reduction of surface and skin friction drag is essential to reduce fuel consumption. The importance of drag reduction is such that even natural creatures have evolved over the time to reduce the drag. In case of shark, the whole body is covered with micro-riblets which lead to significant reduction in drag. This is called “shark skin effect”. It was observed that these riblets over the body of shark lead to around 8% reduction in fluid drag. Similar to sharks birds have evolved over time to reduce the air drag during flight. The streamlined shape of birds and the presence of hollow shaft of feathers are evidence of the evolution of bird structure over thousands of years. In birds the presence of herringbone riblets of feathers has substantial role in drag reduction while flying. In feathers of birds due to the perfect linking of barbs the herringbone riblets are able to align along the shafts of each feather thus reducing the drag considerably. Huawei chen et al [5] have conducted Scanning Electron Microscope(SEM) analysis of microstructures of secondary feathers of pigeons and thus obtained structural parameters by statistical methods. Huawei chen et al [5] have proposed the biomimetic herringbone riblets having narrow smooth edges for getting surface drag reduction.

While in a gliding flight the bird wings show a dihedral configuration as shown in figure 2. The dihedral is in the shape of a V-attitude. It is possible for the birds to alter and vary the dihedral of their wing thus having an effect on their flight performance. By varying the dihedral an effect on lateral-directional stability is also seen. The amount of dihedral shown by different birds varies greatly. Some birds create small V-attitudes and only in certain portions, like outer, of the wing dihedral is present. When the V-attitude angle made by the bird is in downward direction it is referred to as anhedral. But there are birds like herons, pigeons which show very large values of V-attitude angles. The reason for exhibiting large values of dihedral may be related to efficient manoeuvres and improved stability during flight. Also it has been seen that while gliding at low speeds extremely large values of V-attitude angles are used by birds. Birds that exhibit large dihedral are also seen to have rotary oscillations in the roll axis. To study the aerodynamics of bird wings having large dihedral it is important to develop sophisticated aerodynamic methods. It becomes difficult to analyse the aerodynamics of large dihedral in wings because of the high V-attitude angles which produce a 3D flow field. The 3D flow field is a result of the mutual interference between both the wing halves in case of large dihedral. Gottfried sach et al [6] have given an aerodynamic method that can tackle with the problems in analysing high dihedral of wings. Using the proposed method it will be possible to study large dihedral bird wings and aerodynamic data can be generated for such wings. Large dihedrals were found to have substantial impact on the flight of a bird and significant change in the lift and drag characteristics of birds having large dihedral wings was seen.
Designs inspired from nature have been used for long time for constructing air vehicles. Most of the designs being used today have been inspired from nature because nature finds the most efficient designs that can be made. Inspite of putting in best efforts to mimic nature’s best flyers the man-made air vehicles have hardly attained the effectiveness and agility of natural flyers. It is well known fact that the body structures of all the species on earth have evolved over millions of years of evolution. By the way of evolution nature establishes the law of survival of the fittest. The process of evolution of any species gets affected by a number of factors including physical restraints like camouflage for protection from predators, mating etc. One feature that has remained same in all natural flyers over the years of evolution is the use flapping wings for flight. The reason for flapping wings to be used by most of natural flying animals can be accounted to the low Reynolds number effect. Natural flyers fly in low Reynolds number region thus the phenomena of unsteady aerodynamics and viscous forces need to be considered as they affect bird flight. Benefit of flapping wing is that they have the ability to generate additional aerodynamics force for flight via unsteady flow mechanism. Aspect Ratio (AR) plays a major role on the performance of flapping wings. More lift is produced with wings of high AR. Jua-Jiang Fu et al aims to study the effects on aerodynamics of natural flyers due to the structural traits of their body especially wings. For the experiment rectangular wings having AR 1, 2 and 4 were chosen that performed at their wingtips hovering sinusoidal kinematics. Results of the experiments conducted showed that the AR had no effect on the values of force coefficients.

The aerodynamics characteristics of a bat differ greatly from that of birds and insects. This difference is mainly because of the difference in the body structure of bats and other flying animals. In order to generate high aerodynamic forces, the wing of a bat undergoes complex deformations and this makes the flight features of bats different from that of birds and insects. Creating camber along the chordwise direction, twisting of the wing from root to tip, variation of wing area etc. are some of the actively morphing techniques that bats use. It was found that twisting of the wing and cambering in bat wings have effect on the high thrust and lift generation respectively. During flight of a bat the overall wing morphing leads to creation of maximum lift and thrust during the downstroke only. During an upstroke negligible amount of thrust and lift forces are generated. The ability of bat wings to change its area and bend results in amplification of positive force in a downstroke and reducing the negative forces for an upstroke. When considering flight of birds and insects wing deformations are neglected while studying mechanisms for aerodynamic force generation. Wing deformation is a major mechanism for aerodynamic force generation in bat flight and hence cannot be neglected as in case of other flying animals. Bat is one of the few species of flying animals which uses new mechanisms along with flapping wings and hence bat flight attracts a lot of attention from researchers and scientists. Yonglian Yu et al [8] used several morphing models and flapping models to compare the aerodynamic forces generated by them. It was found that a twisting wing increases the lift along with decrease in the fluctuations for an entire stroke. The cambering wing has the ability to significantly increase the lift generated.
The origin of avian flight has been debated for long because of lack of critical information like traditional fossils which are required for documenting the origins of avian flight. The study of fossil remains of extinct organisms has been the only way to study the origin of flight. Researchers started debating about the origin of birds in 1861 after a skeleton of *Archaeopteryx* was found in Germany. After obtaining data from hundreds of preserved fossils of small coelurosaurids and birds it was suggested that the beginning of avian flight was from trees (tree-down theory) and not ground (ground-up theory). The fossils discovered so far show that adaptations have taken place that are necessary in order to enable wing-assisted climbing on trees. By studying traditional fossils Sankar Chatterjee et al [9] have been able to identify six stages of evolution of avian flight. These include arboreal leaping, parachuting, monoplane gliding, undulating flight, and manoeuvring flapping flight. It has been proposed that during arboreal life brain enlargement took place along with an increase in visual activity leading to development of more sophisticated vision. Sankar Chatterjee et al have developed a computer model for simulating flight performance of protobirds that will help in supporting the arguments for evolutionary pathways. The emergence of powered flight in birds has been a key adaptation for birds. Flying requires relatively less energy as compared to walking and running. Flying helped birds in escaping predators and allowed them to explore new resources and seasons thus making them more versatile than other dinosaurs that walked on earth.

A number of species of flying birds exist and every species have their own flight style. Medium to large birds like pigeons, swans etc. fly with their wings continuously flapping and have nearly constant frequency, amplitude and flying speed. Other varieties of small birds follow intermittent flight strategies like ‘bounding’. Bounding refers to quick, high-amplitude periods of flapping interspersed with bounds. While carrying out bounding flight the wings remain firmly stuck to bird’s body. Small birds like woodpeckers and little owls generally carry out bounding flight. But it is not necessary for small birds to bound in order to fly and many small birds never bound. Birds of medium and large size fly using a different intermittent flight style known as ‘flap-glide’. In flap-glide, during periods between flapping the body of bird gets supported by outstretched gliding wings. Flap-glide has been used as a characteristic flight style by predator birds like eagles. During normal direct, level flight also eagles use flap-glide. Again it is not necessary for all large birds to use flap-glide as can be seen in the case of geese and swans which flap continuously while in air. In general it has been seen that aerodynamically economical flights are steady and levelled. But in many small birds it was observed that flapping and bounding styles of flight are far from being aerodynamically or mechanically optimum. Also flap-glide style when used for cruising flight doesn’t show aerodynamic efficiency. James Richard Usherwood[10] aims at considering cost of muscle activation in terms of physiological cost. Also a wide range of aerodynamic and geometric constraints have been considered by James Richard Usherwood[10] to account for energetic advantages. It was observed that in small birds that use bounding have to experience high costs due to activation of muscle for power while contracting. On the other hand the strategy adopted by flap-gliding birds reduces the physiological cost of work.

It has been proved by scientists that bumblebees do not produce sufficient lift from their wings needed to support their weight. As the lift generated is less than required, technically bumblebees should not fly. But on the contrary, bumblebees fly effortlessly in nature thus giving rise to a new set of controversies. There are many such insects like bumblebees which theoretically don’t produce enough lift to fly but they do fly. This makes researchers question the effectiveness of conventional aerodynamic theory in predicting the lift force of these insects. In the case of bird flight quasi-steady assumption is valid and works effectively. For insects the quasi-steady assumption fails and needs to be discarded because of constraints in its application. For example in an insect if the value of lift coefficient, that is needed to provide sufficient lift, is greater than lift coefficient value for normal airfoil then quasi-steady assumption is discarded. Further for applying quasi-steady assumption it is required that the wing travels in air a distance equal to a few wing chords. Hence, conventional
aerodynamic theory is rejected in case of flight analysis of most insects. For a flapping hawkmoth and a mechanical insect, Anders Hedenstrom[11] studied and compared flow visualisation around their wings. The results obtained explain the reason behind the ability of most of the insects to stay airborne. Novel unsteady mechanisms were found to satisfactorily explain the insect flight. In case of flapping wings the induced downward has fluctuating nature and this is referred to as unsteady mechanisms.

For a normal thin wing kept in an incompressible flow the lift slope coefficient is \(2\pi\). For this wing the position of Aerodynamic Center (AC) is calculated to be at the quarter-chord point. These results for a thin wing are calculated after making a suitable assumption that the thin wing in consideration is impermeable. But in nature not all wings are necessarily impermeable like the bird wing. In a bird wing the aft portion is made up of feathers and thus becomes permeable to air. Earlier aircrafts also used to have wings having unpainted paper over them thus making them permeable surfaces. Gil losilevskii[12] studies the effects of permeability of a wing surface like the position of AC in permeable wing surface etc. For experiments Gil losilevskii[12] considers a thin wing section, kept in steady incompressible fluid flow, made up of impermeable forward portion and having permeable aft region. Values of coefficient of lift and pitching-moment (\(C_L\) and \(C_M\)) of this wing are found using closed-form relations. The results obtained show that with increase in the permeability the value of lift slope coefficient decreases. The AC for the wing in consideration changes its conventional position from quarter-chord point of wing to quarter-chord point of forward part. If the forward part has width less than half the chord then AC first goes backward and then moves to the forward portion.

Hao Liu [13] aims to carry out rigorous and integrated modelling of flapping flight of insects for simulation. The natural flyers like insects perform flapping wing style because it helps them create both lift and thrust required for staying aloft and moving forward respectively. Flapping allows insects to carry out amazing manoeuvres along with periods of rapid acceleration and deceleration. Insect flight is generally carried out at moderate Reynolds Number having unsteady motions due to large vortex structures and flexible-wing structures. A general conclusion about the insect flight is that insects make use of high-lift, unsteady aerodynamic mechanisms resulting from formation of complex vortices. A versatile method was followed by Hao Liu[13] that integrates modelling of realistic flapping wing, realistic wing-body morphology and unsteady flight aerodynamics of insects. The insect flight simulator was validated by considering three insects that perform hovering flight. The insects were hawkmoth, honeybee and fruitfly and these were tested for Reynolds number ranging from order of \(10^2\) to \(10^4\).

Birds fly using different flight styles depending on the conditions of surrounding, need and the path they have to follow. Gliding, soaring and flapping are a few styles that the birds commonly use. In gliding the bird keeps its wing held out to the side of body and no flapping takes place. This flight is similar to a fixed-wing flight. In soaring height of the bird remains constant with respect to the ground. During soaring the bird uses rising air current in order to climb without even flapping the wings. Flapping is the most common style which we see in birds and it involves a downstroke and an upstroke. During downstroke most of the required lift is produces while in upstroke very little or negligible thrust is produced. Mehdi ghommem et al [14] investigates for two birds namely the Giant Petrel and Dove Prion the effect of wing morphing on the flight dynamics. The experiment is carried by flow simulation over rigid and morphing wings. The simulation results of rigid flapping wings show that for generating sufficient lift the wing root of the bird should be kept at a particular angle of attack. It has been observed that birds use active wing morphing techniques like twisting and bending in order to considerably increase the thrust produced. Hence wing morphing helps in increasing the amount of thrust generated. For calculating the aerodynamic power and forces 3D Unsteady Vortex Lattice Method was used for simulating flow over the flapping wings in consideration.
Among vertebrates the maximum amount of O₂ requirement has been shown by the flight muscles of hummingbird. The flight muscles of a humming bird are large when compared to flight muscles of other birds. In a humming bird the pectoral muscles (small and large) account for around 25% to 30% of body weight. In other birds the pectoral muscles account for a maximum of 17% of body weight. The down-stroke wing depressor M. pectoralis generates maximum amount of power for flight. The pectoral muscles of hummingbird possess high aerobic capacity. In case of hummingbird critical structural determinant for supplying O₂ are the capillary-to-fibre geometrical relations. The volume of capillary and the surface available for exchange depends on the capillary length per fibre volume. The O₂ flux rates are determined by the size of the capillary-to-fiber interface. O. Mathieu-Costello et al [15] conducted investigations on the structural characteristics for high O₂ flux in case of humming birds. The hummingbird’s pectoralis and supracoracoideus muscles were prepared for electron microscopy and then analysis was conducted for morphometry. It was found that the capillary-to-fiber interface was high in the muscles.

Vast number of computational and experimental research work has been conducted on the insect flight. The failure of conventional aerodynamic theory i.e. the Kutta-Joukowski theorem to explain the flight of insect has already been proved. The insect flight has been an intriguing subject of research because of the large amount of lift that the small wings of an insect produce. The motion while carrying out normal hovering flight consists of nearly constant mid-stroke translational velocity and wing rotation near wing reversal. Unsteady forces created during the hovering motion are the cause for Phenomena like dynamic stall, rotation, acceleration and wing-wake interaction. While studying hovering flight the wing is considered to be rigid. Lin Du et al [16] have numerically investigated the hovering flight by taking the wing as freely vibrating in the vertical direction. By using immersed boundary condition the 2D Navier-Stokes equation had been solved.

Similarities have been found between the evolving Nectarivorous bats and the humming birds in order to be small in size and feed on floral nectar. It has been seen that nectar bats (Glossophagasoricina) during feeding are capable of carrying out hovering flight of several seconds which is energetically expensive. Nectar bats directly fuel there metabolism by utilising the immediately ingested sugars and this has been possible due to their strong intestines which are capable of sugar assimilation. Hummingbirds also have similar strong intestinal capabilities for sugar assimilation. The recently ingested sugars supply around 80% of energy required for hovering flight of nectar bats. Given the several similarities that nectar bats and hummingbirds possess, R.K. Suarez et al [17] conducted study to find similarity between the flight muscle of nectar bats and hummingbirds. The biochemical capacities during hovering flight with flux rates were also compared. The results of the study further strengthen the theory of convergent evolution of nectar bats and hummingbirds in terms of physiological and biochemical traits.

Humming bird is one of the smallest bird species and unlike other birds humming bird skilfully performs hovering flight. The special abilities of hummingbird can be attributed to the low Reynolds number (10³-10⁴) flight and unsteady aerodynamics involved. The flight style of a hummingbird resembles more to insects than to birds. But significant dissimilarities exist between the body structure of hummingbirds and insects which shows that these two can never have the exactly same flight style. The unsteady effects in hummingbird flight can be best observed during hovering. Quite a less number of research work has been done on the 3D vortex structures and the unsteady aerodynamics involved. Songyuan Yang et al [18] have presented a study on the Computational Fluid Dynamics (CFD) of the hovering flight aerodynamics of rufous hummingbirds (Selasphorousrufus). On the wing surface of a hovering hummingbird conical and stable Leading Edge Vortices (LEVs) having spanwise flow inside their core were found. In a hummingbird majority of lift was produced due to the presence of attached bound vortex around the wing of hummingbird. Based on kinematic and morphological data a model of rufous hummingbird was made and the governing equations were solved. Songyuan Yang et al have
focused on the properties of wing kinematics, far-field wake and the aerodynamic force that is produced in hovering flight of hummingbirds.

In analysis of flapping wings quasi-steady method has been frequently used. In order to analyse the unique features of flapping wings, modifications have been made in the quasi-steady method to accommodate acceleration effect, rotational force and translational force. Unlike the Computational Fluid Dynamics (CFD) models the quasi-steady model cannot explain 3D flow pattern but the quasi-steady model conducts analysis in very less time. Jialei song et al [19] has presented a quasi-steady model that describes the hovering flight aerodynamics for a Ruby-throated hummingbird. The quasi-steady model was developed in order to study the limit of low-order model in representing flow physics of birds. For the model real-life wing kinematics were taken. CFD simulation of a revolving-wing model was used to calibrate the quasi-steady model. It was observed that the quasi-steady model was able to accurately calculate the lift production but failed to account for the forced oscillations.

Hummingbirds are different and distinctive when compared to the other bird species. The reason for this has been closely related to the evolution of the hummingbirds primary source of energy i.e. the floral nectar. The evolution of hummingbird has been greatly affected by the presence of floral nectar around the hummingbirds. A number of changes came in the form and function of hummingbirds like changes in anatomical and locomotors systems. Douglas warrick et al [20] describes how various pressure and constraints of nature shaped the evolutionary cycle of hummingbirds. While removing nectar from the flowers flying is preferred compared to landing but for this the locomotor system of the hummingbird must operate continuously and precise modulation is needed for safe approach and steady feeding. Hovering flight is unconditionally the most energetically expensive phase of flight compared to any intermediate forward flight. Birds reduce the energy expense by spending less time while hovering. Due to limited quantities of nectar produced by flowers the evolution of hummingbird led to adopting small body sizes to reduce energy consumption. Small size isn’t the only solution to reducing energy consumption. For providing weight support the recovery stroke of wings has negligible contribution. For small hovering birds like hummingbird double the weight support must be produced by the downstroke.

It has been observed and suggested by many researchers that a hoveringbird can more quickly move from one flower to another compared to the birds that perch. But this ability comes at the high cost of energy that hovering requires compared to perching. Graham H. Pyke[21] has aimed at estimating this trade-off between speed and cost for the perching honeyeaters and hovering hummingbirds in two filed situations. Australian hummingbirds (Trochilidae) and Australian honeyeaters (Meliphagidae) are ecologically similar but differences exist in their foraging behaviour. While foraging hummingbirds always hover at the flower and then collect the nectar. But the honeyeaters are found to perch at the nearby stems while collecting nectar. The character of hovering and perching is found to have relation with the body size of the respective birds. In general honeyeaters are found to have larger body size compared to the hummingbirds.

When considering natural low-altitude hovering flight the first species that come into mind are the honeybees. Honeybees have the marvellous capability to fly effortlessly through the harshest of climatic conditions. Earlier researches focused on study of insect flight in well and clean environment but the need to develop water repellent surface made scientists to observe the flight of honeybees in dew and mist conditions. Youjianliang et al [22] used high-speed cameras, to record the flight of honeybees through mists and drizzling rain, in order to study the mechanism behind the incredible flight of honeybees through these rugged environmental conditions. Atomic force microscopy and scanning electron microscopy was used by researchers to study the microstructure of the wings of honeybees. The wings of honeybees were found to remain dry even on exposure to steam. In case of honeybees it was found that the hydrophobicity not only depended on the wing topography but also on the chemical constituents of the wing. It was found that on the body of honeybees the amount of
hydrophobic proteins was more than that of hydrophilic proteins. The results showed that the wings of honeybees have rough surface with distribution of bristle on both dorsal and ventral sides. Presence of hydrophobic protein containing minimum of one hydrophobic tetra-peptide was discovered on the honeybee wings. The structure and chemical composition of wings of honeybees will help in discovering new and advanced hydrophobic structures.

High altitude flight offers several advantages along with challenges to the natural flyers. Ecological advantages offered by the high-elevated habitats include decrease in competition, reduced risk to predation etc. Along with these benefits the disadvantages of high-elevation flight include physiological challenges because of reduction in density of air and oxygen availability. The constraints that high-altitude flight offers severely affect various manoeuvring capabilities of the birds. These flight manoeuvres are necessary for birds in order to escape predators, compete with rivals and foraging. To study impact of high altitude on individual manoeuvres of the birds, Paolo S. Segre et al [23] calculated the free-flight styles/manoeuvres of male Anna’s hummingbirds. Initially performance was measured by placing hummingbirds in a large chamber kept at high altitude and later the chamber was translocated to a low-elevation. For studying the large number of manoeuvres performed by the hummingbird a multi-camera tracking system was used. The manoeuvres were studied on the basis of body position and orientation. It was found that when flying at high-altitudes the translational and rotational velocities of hummingbirds decreased and the birds refrained from carrying out demanding turn. For determining the effect of mechanical and metabolic constraints separately another experiment was performed by Paolo S. Segre et al in which the hummingbirds were placed in an airtight chamber. normoxicheliox or nitrogen was infused in the chamber. It was observed that hypodense treatment resulted in reduction in hummingbird’s performance but the hypoxic treatment has negligible effect on manoeuvring of birds.

By using adaptation capabilities butterflies have the ability to fly effortlessly by maintaining the required flapping-of-wing flight in extreme environmental conditions like gust etc. Butterflies possess unique adaptive function because of effective interaction between body, nervous system and environment. This adaptive system is called “Mobiligence”. In case of Mobiligence of butterflies the environment is the generated flow field. The objective of Kei Senda et al [24] is to study the stabilisation principle in case of flapping flight of butterflies. The flapping flight of butterflies has rhythmic and cyclic motion. For analysing the aerodynamics of a butterfly an experimental setup was done using a low-speed wind tunnel. For getting dynamic model of butterflies flight Lagrange’s method was used. The validation of the model was carried out upon comparison with experimental data. Senda et al studies the impact of wake-induced flow and torsional wings on the stability of a butterfly flight. The results suggest that the wake-induced flow and torsional wings lead to reduction in the flight stability.

During 1980s it was discovered that the insect wings possess deforming ability and this has significant effect on their flight. The studies done found that wing morphology, kinematics and the flight behaviour of an insect were closely related to each other. The storage of elastic power is essential element in case of insect flight and without storing elastic power insects cannot fly. For decreasing the complexities involved in calculation and modelling most of the studies done on insect flight have assumed the wings of an insect to be rigid and flat. T.T. Nguyen et al [25] modelled a wing and then studied the effect of wing flexibility on aerodynamic performance of the modelled wing. Initially the effect of distribution of stiffness property on the deflection under static and inertial loading was analysed. Wings having Leading Edge Reinforced (LER) was found whose deformation on trailing edge resembled to that of the insect wings during flight. In LER type wings the stiffness was found to reduce significantly towards the tip of the wing. The class of LER type wings was found to be superior to rigid wings in terms of aerodynamics.
Igor Kovale[26] has experimentally studied the effect of presence of hollow region in butterfly \textit{Pyrameisatalanta}. Presence of complex microstructure was found on the butterfly scale and it was seen that higher lift is generated on the butterfly wings having scales. Movable appendages having size 30μm to 120μm are present on the wing surface of butterfly. The scale of butterfly is resembles a sack of lower and upper laminae as shown in figure 3. Hollow region is present between both the laminae. Trabeculae emerge from the flat plate shaped lower laminae to connect to the upper laminae. 

Butterflies possess some peculiar features like being the youngest insects when evolutionary history is considered. The scale microstructure and appendage mobility of a butterfly have evolved over years of natural selection. The scale microstructure of a butterfly has multiple role like reducing vibrations, regulating body temperature, absorbing the ultrasonic squeaks of predators like bats and reducing the noise. Also the colourful and optical effects on the wings are due to the presence of scales. The wing motion of a butterfly is multi-oscillatory because the wings flaps (about the base) and rotate (about the longitudinal axis) simultaneously. Igor Kovale used two oscillating models for measurement of aerodynamic forces. The experimentally obtained data showed that the presence of hollow region increased the lift by 1.5 times and reduced the damping coefficient by 1.38 times.

The shape and size of wing plays a crucial role in determining the flight performance. Flight performance depends on the number of factors like body morphology, behaviour, physical environment etc. For flying animals having small body size dissipation of viscous effects, due to small perturbation, takes place more quickly compared to flying animals of larger body sizes. For large body, small perturbations lead to significant unsteadiness of the flow fields surrounding the wings. David Outomuro et al [27] aims at exploring the correlation between wing shape and wing size for territorial males of damselfly family Calopterygidae. For the analysis, wing coloration was also included because it was also found to have an effect on wing shape. The analysis by David Outomuro et al was conducted using two techniques namely non-dimensional radius of the second moment of wing area (RSM) and geometric morphometrics. A complex relationship was found between RSM and wind size in damselflies. The complexity of relation can be accounted to wing coloration and specific behaviour (like courtship). The results suggest that taxa-specific relation exists between wing shape and size.

The flight skill of dragonflies is way more than impressive compared to other insects because of the structural and chemical composition of a dragonfly’s wings. In the wing of dragonflies the major structural component are the veins. The veins are joined by resilin having higher elasticity at particular joints. By flapping quickly the dragonflies are able to produce the required aerodynamic force for flight. In case of dragonflies the wings have capability to deform and this has a huge significance during flight. The wings change their shape from time to time in order to have better distribution of aerodynamic forces so that higher lift can be generated. Unlike birds and bats insect
wings (like of dragonflies) don’t possess muscles in main part of the wing. Hence, the deformation of wings in dragonflies is caused by the flight loads, aerodynamic and inertial forces generated due to flapping. Resilin, a hydrophilic protein, was discovered on some vein joints in the wings of dragonflies. One of the classifications of vein joints of dragonflies can be done on the basis of resilin present on the joints. Dan Hou et al [28] created a 3D finite element model of the dragonfly wing. While developing the model soft vein joints were also considered. Studies were conducted on the passive deformations due to aerodynamic loads and active flapping motion. The results showed that the soft vein joints improved chordwise flexibility during passive deformations. During active flapping the rigidity of the wing has to be maintained in spanwise direction in order to achieve required amplitude.

Humans have taken inspiration from nature to invent and develop new systems that are more efficient and have better capabilities than the existing systems. Nature always finds the best of the designs and systems to incorporate the most efficient structures. Even after a century of successful development in aircraft structures, the mechanism of flight by natural fliers is very impressive and more advanced than some of our best aeronautical structures. G.K. Suryanarayan et al [29] formed the aerodynamics of dragonfly as the basis for developing passive configurations in order to generate steady lift. While carrying out forward flight the fore-wings of a dragonfly flap alone while the aft wings remain stationary. This mechanism shows that there must be some aerodynamic coupling between the fore and aft wings while having a forward flight. In order to mimic the flapping of the fore-wings, the fore-wings were replaced by a cylinder because the cylinder is known to shed discrete vortices. The cylinder was used in combination with a flat plate kept downstream and below as shown in figure 4. During the initial transients once the shed vortices pass over the plate, it was observed the vortices shedding nearly stops and a trapped vortex is formed over the plate.

![Figure 4. Configuration of cylinder and flat-plate [29].](image)

Richard J. Bomphrey et al [30] has aimed at synthesising and enhancing the knowledge available on dragonflies and damsselflies relating to their mechanics and aerodynamics of flight. Significant amount of data like dragonfly wing morphology, gliding flight aerodynamics, aerodynamic efficiency etc. has been collected. New techniques like laser-line mapping of wing topographies, computational fluid dynamics simulation of wing morphologies, particle image velocimetry etc. have been used. The determination of homologous structure in dragonflies has been a challenging task primarily because of complex muscle arrangement. Most of the muscles in dragonflies and damsselflies inert on the radial veins thus giving the insects ability to actively control angle of attack, camber, twist etc. Vein curvature, vein cross sections (that promote torsion but resist bending) etc. passively control the regional positioning of the wing. The wings of dragonflies are not smooth surface and corrugations are present all over them. These complex geometries on the wing surface provide sophisticated mechanical advantages to resist longitudinal bending.

The independent four wings flapping of dragonflies allows them to manoeuvre effectively during flight. Carnivorous predators like dragonflies are capable of preying and mating during flight itself. The dragonflies have complex flapping mechanism because they can control both their forewing and hindwing separately. Depending on the mode of flight a dragonfly can vary the phase angle between
the forewing and hindwing. Unlike most insects the dragonflies can precisely manoeuvre and accelerate because they have direct musculature control of the wings. Hidetoshi Takahashi et al [31] using a flying ornithopter established that the phase angle control effects the aerodynamic performance. The phase angle of the designed ornithopter varied according to phase lag between slider-cranks of forewing and hindwing. Microelectromechanical differential pressure sensors were installed, on the centre of both forewing and hindwing, for calculating aerodynamic performance during flapping motion whenever change in phase angle takes place. The phase angle was varied both in tethered and free-flight condition and the results showed that performance of forewing remained nearly same while the hindwing showed variation in the performance. The conclusion of experiments was that a flying ornithopter can control flight force balance by simple changes in phase angle.

Dragonflies are well known for their agility, endurance and predating capabilities. Dragonflies can fly at low-speeds, hover and even fly backwards. In evolution insects generally reduced a pair of wings but dragonflies and damselflies have retained their distinctive four-winged form. Unlike other insects in dragonflies direct musculature acts at the wing base that allows the dragonflies to have direct and independent control of each wing. It has been found that four wings are not very helpful in lift generation. James R. Usherwood et al [32] has used a mechanical model of dragonfly to show that even after not being suitable for lift generation, four-wing configuration is aerodynamically efficient for flight. The two pairs of wings of dragonflies become aerodynamically efficient by extracting energy from the wake that gets swirled. It was found that by appropriately phasing fore-hind wing the power required can be reduced by 22% when compared to single pair of wing configuration.

Researchers have been able to study the unsteady aerodynamics involved in hovering flight of insects but the aerodynamic effects of wing deformation have still not been investigated because of lack of analysis methods. For analysing the lift generating mechanism while hovering considering wing deformation was not important as the generation of force takes place near the wing tip. But passive wing deformation is a crucial factor that needs to be considered while analysing flapping flight. Masaki Hamamoto et al [33] developed a free-flight simulator using Fluid Structure Interaction (FSI) and Finite Element Analysis (FEA) based on Lagrangian-Eulerian method. The simulator can quantitatively study the correlation between wing deformation and its surrounding flow. The numerical model of the dragonfly could do rapid turning at 1200 degree per second of yaw angular velocity which was inspired by flapping motion in nature.

Aerodynamic lift generation for insect flight has been studied in both quasi-steady and unsteady regimes. During hovering flight aerodynamic drag has no role in vertical force. Some of the finest hovering insects like dragonflies and hoverflies use inclined stroke planes where the downward and upward drags don’t cancel out each other. By computing an ideal dragonfly wing motion it was found that for supporting about three quarters of its weight the dragonfly uses drag. Hovering insects fly at large angle of attack in order to generate high transient force by taking advantage of dynamic stall. Z. Jane Wang [34] for investigating the generation of force and energy consumption during hovering flight studied wing motion where inclined angle of stroke plane was taken as the parameter. The results suggest that because of the flow being severely stalled the lift and the drag are nearly same. The aerodynamic efficiency was found to be same upto an inclined angle of 60 degrees.

Most of the biological flyers have flexible wings which allow them to perform acrobatic tasks in air. The 3D deformations and kinematics of the wings have significant impact on the structural, aerodynamics and control aspects of insect flight. Scientists believe that new mechanisms can be discovered for lift generation by properly studying the wing flexibility and deformation techniques from nature. Christopher Koehler et al [35] have suggested a subdivision surface reconstruction method which can reconstruct the wing deformations and kinematics of flying insects. The method
does not consider the wing as rigid. The muscles near the root of wing were used for inducing chordwise camber in the wing’s portion near the specimen’s body.

The wings of a dragonfly function as ultralight airfoils during gliding. For static reasons the wings of dragonflies are having cross-sectional corrugation which forms valley where rotating vertices develop. The configuration of this cross-section varies along the longitudinal axis of the dragonfly’s wing. Due to such variation there exist different aerodynamic characteristics locally on a wing. When the $C_L/C_D$ ($C_L$ and $C_D$ refer to coefficient of Lift and Drag respectively) characteristics were analysed by Antonia B. Kesel et al [36] Reynolds number 7880 and 10000 by using a force balanced system it was found that the cross-sectional geometries produce drag as low as that of a flat plate. The value of $C_{D,min}$ goes below 0.06. But unlike flat plate the wing profiles are able to generate much higher lift. The lift forces are comparable to technical wing profiles when placed in low Reynolds number. Because of rotating vertices along the chord it was found that the pressure relationship along the profile changes when pressure measurements were done at Reynolds number of 9300.

Many aspects of insect flight are affected by the 3D dynamic shape of flapping wing. The deformations of the wing are controlled by architecture of the wing. The study on flexural stiffness of the insect wings hasn’t been extensively done yet. S.A. Combes et al [37] have designed a method to measure the displacement along the wing when a point force was applied. This method was used to measure flexural stiffness variation for the hawkmoth Manduca sexta and the dragonfly Aeshna multicolour. Flexural stiffness was found to rapidly decrease from the wing base to the tip and from leading edge to the trailing edge. The rate of variation is approximately exponential. The finite element models of Manduca sexta forewings show that while transferring bending to the edges in proximal regions the rigidity is preserved by flexural stiffness.

Presence of Leading Edge Vortex (LEV) was found above the wings during the end of downstroke. Richard J. Bomphrey et al [38] have presented the first of its kind Digital Particle Image Velocimetry (DPIV) analysis of the flow field around wings of Manduca sexta. The smoke visualisation and DPIV result analysis matches with the experimental results of flow visualisation experiments done before. The experiment provides the flow field above the thorax. Upon study it was found from detailed DPIV results that by the end of downstroke the structure of LEV is same as that seen in free flying insects. According to DPIV results the magnitude of velocity for spanwise flow in the LEV is less than 1ms$^{-1}$.

Flapping flight aerodynamics has been the area of interest for researchers for a long time and the design of man-made aircrafts are somewhat primarily inspired from the nature. A major task in designing the Micro-Air Vehicles (MAVs) is to simulate the flapping flight of natural flyers. The flapping flight of insects (or MAVs) operates via non-conventional mechanisms for increasing the aerodynamic loads and this is done by creating unsteady and nonlinear flow fields. It is know that Leading Edge Vortex (LEV) is used as a high lift mechanism by insects. The same principle is also used for lift generation in the case of highly swept and delta wings of manmade aircrafts. During LEV the bound vortex is augmented on the wing leading to left generation. LEV is similar to dynamic stall phenomena where a rapid variation in Angle of Attack (AOA) of the wing is seen. But unlike dynamic stall the LEV has stable nature owing to the outward spanwise flow that convects the LEV towards the wing. The generation of spanwise flow in insects takes place via rotational motion that creates spanwise velocity gradient. During insect flight it has been found that LEV is the major mechanism for lift production but two other mechanisms are also there namely rotational lift and wake-capture effects. Haithem E. Taha et al [39] has presented for the aerodynamics of flapping wings a state-space representation. Duhamel’s principle has been used on non-conventional lift curves in order to find the contribution of LEV. The validation of the model proposed was conducted by comparing it with Navier-Stokes simulation for hovering insects.
The attempts to develop a Micro Air Vehicle (MAV) started back in 1997 because of the limitations of available class of surveillance flying vehicles like UAVs, satellites etc. These vehicles do not possess the capability to enter inside buildings and carry out espionage activities. For such purpose there has been the need to develop advance MAVs which are easily portable and can function in any type of dull and dusty surrounding. The idea for developing and designing of an efficient MAV comes from the flapping flight of insects. Wing designing for a MAV is a complex task and a number of aerodynamic effects need to be considered. This is because in an insect the wings perform the combined task of generating lift, propulsion and manoeuvres simultaneously. The flapping wings function both as lift generating device and also as propulsion system and due to this complex aerodynamics comes into effect. Hence there is need for an aerodynamic tool that can help in studying the parametric design space and coverage on more than one configuration. S.A. Ansari et al [40] aims at conducting a review of the aerodynamic modelling approaches that have been used till now. The approaches have been categorised into steady-state, quasi-steady, semi-empirical and fully unsteady methods.

Gunther Pass has reviewed the biological composition of the wings of an insect. Wings of an insect are mostly made up of lifeless cuticles. The veins in the insect wings have a number of tissues and sensory systems present in them. These tissues need regular supply of oxygen and other nutrients. Gunther Pass [41] has surveyed about the role of tracheal and circulatory system in transporting the required minerals to the wings. In case of most of the insects circulation via veinal network is done by hemolymph. Researchers are still studying the technique used by insects for providing hydration to the wing cuticle so that the cuticles don’t lose their flexibility. Wing has fascinated researchers the most because it a delicate body structure but still allows the insects to fly. For controlling wing movement and body stabilisation the sensory organs on insect wings are mechanoreceptors. There are also insects in whose wings sound pressure mechanoreceptors are present which helps them in intraspecific communication. The mechanosensation is a crucial multimodal sensory input because it helps the insects in quick collection of information and its further processing. The wing mechanoreceptors not only function during flight but also during periods of inactivity of insects. Maximum number of mechanoreceptors is present on the joint region between the thorax and wing base. Also there are mechanoreceptors present on the wing blades.

Jennifer L. Palmer et al [42] describes the methods for studying and developing aerodynamic tools that are necessary for design and development of a bio-inspired Micro-Air Vehicle (MAV) that is fully mission capable. There are various challenges that come in the way of designing a fully-functional MAV for surveillance that has flying qualities of natural flyers like insects. The researches done on MAV were categorised into analytical, experimental and numerical investigations that will help in making a flapping wing MAV. Numerous MAVs have been developed till date but not even single one of them can match the hovering and flight capabilities of naturally flying insects. Jennifer L. Palmer et al has focused on the aerodynamic characteristics of MAVs like the forces and moments that wings generate. The design and control of a bio-inspired MAV is affected by the set of wings having a particular shape and structure. The mission capabilities like stability, endurance etc. of a MAV are constrained by the aerodynamics of the system. Figure 5 shows the testbed developed for aerodynamic testing. The challenges involved in MAV designing include wing arrangement like the number and position of wings. Other challenges include flapping mechanism which should have particular wing kinematics, flapping rate etc. Conducting a scaling analysis of natural flying species that do hovering flight allows researchers to formulate basic rules for flapping-wing MAV designs. Observations suggest that a viable design for flapping wing MAV is a simple four-wing device having basic wing design. The MAV will have single active axis for flapping.
A new exceptionally small Nano Aerial Vehicle (NAV) was being designed based on nature. The NAVs have a vast range of new capabilities to offer compared to Micro Aerial Vehicles (MAVs). As the work in NAV started very rapidly proper study could not be done to explore the properties of MAV. Mohd. Firdaus Bin Abas et al [43] have reviewed the latest development of MAV like kinematics and membranes. Mohd. Firdaus Bin Abas et al had also studied the probability of using piezoelectric transmission for the flapping wings.

The information sensing and gathering techniques will be revolutionised by the use of Micro Air Vehicles (MAVs). W.Shyy et al [44] has aimed at reviewing the work done in aeroelasticity and flapping wing aerodynamics. A change in Reynolds number suggests a change in Leading Edge Vortex (LEV) and spanwise flow structures. Wing tip vortices lead to energy loss in stationary wing theory. But these tip vortices interact with LEV during flapping flight to increase lift produced. With decrease in the size of MAVs, fixed wing designs are not working and face serious problems like flight control and lift generation.

Hao Liu et al [45] have conducted a study relating to aerodynamics of flexible wings and stability of passive flight dynamics. The study has been done on a flapping Micro Air Vehicle (MAV) by combining force evaluation, kinematics of flapping wings and computational approach. The prototype of MAV has weight of 2.4g-3.0g and has X-type wing with wingspan of 12-15cm. For evaluating the flexible wing performance of MAV dynamic flight simulator has been used. The flight characteristics of MAVs are substantially affected by the surroundings due to MAVs being light weight and low speed aerial vehicles. The fluid and structural dynamics of a MAV are interrelated and thus making the analysis of whole MAVs difficult task. The dynamic simulator used provides the MAVs evaluation in terms of vortex and wake structures.

SriyuliantiWidhiarini et al [46] have proposed a Micro Air Vehicle (MAV) having up-down and twisting wing system like birds. The development of Flapping-wing Micro Air Vehicle (FMAVs) resembles the bird flight very closely. FMAV discussed has a wingspan of 50cm and double-crank drive system. The abilities of FMAV was significantly increased by adopting several features from birds like bird-mimetic wing shape and an up-down and twisting wing drive mechanism. By installing flight control computer autonomous flight system was implemented. A reduction in effective angle of attack and presence of 3D flow structure during flight was found due to the small size of FMAVs. This makes the vehicle sensitive to gust and other disturbances. Experiments in wind tunnel showed that FMAV having high-camber wing and double-crank system produces more lift.
Akira Obata et al [47] have presented a deep study of low-speed flow for the designing of ultra-light dragonfly. In designing the flying robots special attention was given to the gliding capability of dragonflies. One of the major obstacle in constructing ultra-light dragonflies is the increase in viscous flow at low Reynolds number. The reason for dragonflies being superior flyers is the corrugated wing structures and thus this can be used in developing the flying robots. The dragonfly configuration of the flying robots was found to have higher compatibility with high lift devices and propellers used. Development will allow scientists to expand the flight envelope of a flying robot.

Du CP et al [48] has investigated the modelling and control design of a dragonfly based Micro Air Vehicle (MAV) which has flapping wings. Initially for the flapping wings an aerodynamic force model has been developed. The model was developed using wing’s local air velocity and local angle of attack. At last for the flapping MAV an entire mathematical model was developed by relating kinematic model and aerodynamic force model. The MAV developed is taken to be a six degree-of-freedom body. In order to successfully mimic the dragonflies the tail of MAV can only swing instead of having proper control surfaces like other aircrafts. The controller iteratively solves for desired control signal by using Newton-Raphson method.

Insect species like dragonflies, damselflies etc. use wings that are pleated along the chord. The insect wings are very light and membranous thus allowing them to support different aerodynamic and inertial force. The benefit of having pleated framework is resistance to span-wise bending. Dragonflies fly in ultralow Reynolds number regime that ranges from $10^2$ to $10^4$. Shwetanshu Gaurav et al [49] have conducted extensive numerical simulation of fluid dynamics based on the pleated wing section of AeshnaCyanea. The experiments had been done in ultra-low Reynolds number region in order to find potential application of pleated airfoils in Micro Air Vehicle (MAV). Number of vibrations and forces are seen whenever the wings of a dragonfly interacts with the surrounding airflow. The results suggest that pleated airfoils generate higher lift and lesser drag leading to an increase in the aerodynamic performance. This suggests that pleated airfoils are a good choice for application as fixed wings in Micro Air Vehicle (MAV) [50].

3. Literature Summary

Researchers have adopted multiple techniques for analysis and evaluation of low Reynolds number flight of animals. These techniques can be broadly categorised into Theoretical, Experimental and Numerical methods. It was observed that scientists have preferred Experimental and Numerical techniques because these methods give more accurate result. Experimental methods give better visualisation of the unsteady aerodynamics involved with low Reynolds number flight.

Modelling of flight aerodynamics was done by researchers which involve estimating the aerodynamic forces acting on a bird in flight. Different methods of modelling were used according to the complexity of the problem. Newton’s laws of motion are applicable to bird flight and hence can be used for estimating bird’s velocity and position. After making certain assumptions basic equations can be used for modelling. First is that the induced velocity is neglected because it is very small compared to freestreamvelocity. Other assumption is that the flow is quasi-steady.

The experimental methods mostly made use of wind tunnel setups. The researchers used to develop a life size of the bird and insect in consideration and then this model was subjected to required conditions in the wind tunnel for approximation. Many times live birds were also analysed by using high-speed cameras. One method that widely used by scientists was Particle Image Velocimetry (PIV).

For generating numerical solution of the bird aerodynamics a series of steps need to be followed. First domain discretisation has to be done and then the flow properties need to be evaluated for each cell of the respective domain. The domain discretisation can be done using ICEM-CFD and for enhancing mesh quality, mesh smoothing process can be carried out. Smooth mesh will ensure that the
solutions converge quickly. Many papers used FLMNAV solver for carrying out computations. FLMNAV is based on finite volume approximation. Numerical methods also include carrying out simulations where unstructured triangular mesh was employed which is based on finite volume approximation. The software used was ANSYS-14.0. Navier-Stokes equation has been widely used for numerical solutions.

4. Conclusion and Future Scope

Low Reynolds number biological flyers use flapping wing mechanism for flying and this allows them to fly effortlessly with minimum resistance. For example birds experience G-forces of about 10-14G regularly whereas the best military aircrafts can experience a maximum upto 8-10G. Study of fluid dynamics using simulation has been fast growing to evaluate the aerodynamic effects of natural flyers. Researchers have been preferring to use Numerical and Experimental techniques to investigate the unsteady aerodynamics involved in flight of natural flyers. Various lift generating mechanisms like Leading Edge Vortices (LEV), wake capture etc. are used by birds and insects. Flexible wings reduce the stall and also enhance other aerodynamic characteristics like lift etc. Wind tunnel tests and Particle Image Velocimetry (PIV) have been widely used for flow visualisation and to study flow interaction of flyers with surrounding air. By flapping the wings flying animals are able to create both lift and thrust as per requirement. On keeping the wing simply stretched out without flapping birds are able to produce only lift without generating thrust. Such type of flight refers to gliding flight. The hovering motion of an animal depends on its size, degrees of freedom, moment of inertia etc. Hovering is a technique mostly used by small flyer like birds and insects. Different flight styles from animals can be adopted to design a Micro Air Vehicle (MAV). The study of MAVs becomes difficult because of unsteady aerodynamic involved. Studies are going on to efficiently develop MAV system which have efficiency and capabilities similar to those of natural flyers.

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