CHAPTER 2

REVIEW OF LITERATURE

2.1 INSTIGATION OF THE MAV WORK

The imitation of nature’s flapping wing flight has been humanity’s oldest aeronautical dream. As demonstrated in art and literature, fascinating with flapping flight is one of the oldest human characteristics. Leonardo Da Vinci designed some of the first earnest attempts of ornithopters in 1490. In 1870, Gustav Trouve successfully flew a combustion-powered ornithopter, and a variety of successful ornithopters have been designed and built since then (The Ornithopter Society (2001), http://indev.hypermart.net/about1.html, What’s an Ornithopter). Significant improvement had been made at the University of Toronto, where James De Laurier and his students have built an assortment of successful ornithopters and have recently designed a manned ornithopter (De Laurier 1982-1984).

Hundley Richard et al of the RAND CORPORATION performed the first feasibility study for MAVs in 1993. The authors indicated that the development of insect-size flying and crawling systems could give the significant military advantage in the coming years. During the following two years, a more detailed study was performed at Lincoln Laboratory. This study resulted in a DARPA workshop on MAVs in 1995. In the fall of 1996, DARPA funded further MAV studies under the Small Business Innovation Research (SBIR) program. AeroVironment performed a Phase I study, which concluded that a six-inch MAV was feasible. In the spring of 1998,
AeroVironment was awarded a Phase II SBIR contract, which resulted in the current Black Widow MAV configuration, Davis (1996). Several Universities have also been involved in MAV research. Competitions have been held since 1997 at the University of Florida and Arizona State University. Potentially valuable theoretical work concerning minimum induced losses associated with wing flapping has also recently been done by Hall et al (1994), Hall Kenneth et al (1996), but has not yet been utilized in ornithopter design.

2.2 AERODYNAMIC MECHANISMS

The aerodynamics of flapping flight is quite different from fixed or rotary winged flight for two main reasons: the first is that they act in two different aerodynamic regimes, and the second is that the velocity of the wing or blade relative to the fluid is time-varying.

A clear understanding of flapping flight aerodynamics has been obtained by dynamically scaled models of insect wings that can reproduce the same aerodynamics mechanisms present in insect flight by Dickinson et al (1999). These experiments have unveiled three main aerodynamic mechanisms involved with flapping flight: the delayed stall, the rotational lift and the wake capture.

The delayed stall appears at the onset of motion of the wing (Figure 2.1a-e). As the wing starts moving a small vortex appears behind the leading edge and an asymmetric, opposite swirl appears in the fluid close to the original resting position of the wing as illustrated in Figure 2.1b. The presence of two vortices moving in opposite directions but with identical strength is the equivalent principle of conservation of momentum for fluids. The vortex above the wing creates a lower pressure on its back surface, thus producing a net aerodynamic force perpendicular to the wing surface. As the
wing moves, the vortex behind the leading edge increases along with the aerodynamic force (Figure 2.1 c). However, after a certain distance a new vortex starts appearing behind the trailing edge to keep the total fluid momentum constant (Figure 2.1d). This vortex has a rotation direction opposite to that of the leading edge vortex and in turn decreases the force production. Moreover, the vortex on the leading edge keeps on increasing till it reaches a critical size at which point it detaches from the wing and is shed into the fluid, thus it is decreased the force production even further (Figure 2.1e). As soon as the leading edge vortex detaches, a new vortex starts appearing behind the leading edge and this process of the vortex building and detaching repeats itself endlessly.

![Figure 2.1 Cartoon of Delayed-stall Mechanism](image)

The vortex shedding process appears after the wing has traversed a distance of a few chord lengths; therefore the increased aerodynamic force production can be captured only at the very beginning of the wing movement. Insect wings move only few wing chord lengths when they flap
(Ellington 1999), and thus are able to capture this enhanced force production. Another very important characteristic of flapping flight is that the wings do not translate but rather rotate about their wing hinges. In contrast to the fixed winged vehicles for which large angle of attacks give rise to turbulence, the leading edge vortex is stable for angles of attack up to $90^\circ$. The aerodynamic force generated is an increasing function of the angle of attack. The last important difference of delayed stall relative to fixed-winged vehicles is that the aerodynamic force is almost perpendicular to the wing profile rather than perpendicular to the wing velocity.

The rotational lift mechanism is the result of a combination of the translation and rotation of the wing (Sane et al. 2001). This mechanism is analogous to the one that allows a ball to curve when it is thrown with some spin, as commonly seen in baseball or tennis. In fact, an aerodynamic force perpendicular to the translational velocity appears if the ball has a backspin as shown in Figure 2.2. The magnitude of the aerodynamic force generated by the rotational lift is approximately proportional to the product of the angular velocity and translational velocity.

![Figure 2.2 Rotational Lift for a Rotating Ball and for a Rotating Wing](image)

The last mechanism present in flapping flight is the wake capture. It is present at the beginning of each half-stroke after the wing has inverted its motion and started to move. The wake capture appears when the wing
interacts with the effects of past strokes on the ambient fluid environment. The fluid behind the wing is dragged along with the motion of the wing, as shown in Figure 2.3. As the wing slows down and inverts the direction of motion, it hits the fluid, which is still moving because of its momentum. Therefore, the velocity of the wing relative to the fluid is larger than the velocity of the wing alone, and therefore results in the generation of a larger force. This is a simplified explanation of the principle behind the phenomenon of wake capture. The contribution of each of these three aerodynamic mechanisms has been measured using a dynamically scaled model of a wing. $V$ and $W$ indicate the velocity of the wing and of the fluid wake relative to an inertial frame respectively.

![Figure 2.3 Cartoon of Wake Capture Mechanism](image)

### 2.2.1 Unsteady Wing Lift Theory

From the potential theory, a thin airfoil or plate having either a sudden or a sinusoidal change of angle of attack generates an alleviating lift. The sinusoidal response is given by Theodorsen’s function $C(\omega)$ (1935) for a
sinusoidal oscillation of a wing and Sears’s function \( S(\omega) \) for a sinusoidal gust. More simplified result is obtained by Kussner-schwarz (1941) for sinusoidal gust problem, the expressions for lift is given as,

\[
L = \pi \rho c U h e^{i\omega t} \phi(k)
\]  

(2.1)

\[
\phi(k) = \frac{1}{\sqrt{1+2k\pi}}
\]  

(2.2)

The lift alleviation results from a series of shed vortices left in the wake, which is assumed to be a flat surface parallel to the general flow. By making force measurement of tethered dragonflies, Somp et al (1985) reported that the simple large lift peaks of 15-20 times body weight occurred once in each stroke period and suggested that the lift generation was dominated by integrated interactions between wings rather than by the unsteady effects elicited independently by each of the four wings.

In insects having low-aspect-ratio wings, the effect of unsteady wing motion on the aerodynamic forces and moments becomes predominant at low flying speed. The maximum lift-to-drag ratio occurs at a large lift coefficient, and normally insect flight relies on drag as well as lift at high angle of attack. It is supposed that, unlike the flight of odonata, the strong shed vortex coupled with the separation bubble at the leading edge generates an extremely large aerodynamic force. A low-aspect-ratio wing can generate a much larger aerodynamic force consisting of the lift and drag when the wing is translating with an adequate angle of attack, in the range 30-60 deg.

For a sinusoidal oscillating wing at or near the stall, the aerodynamic reactions vary in a periodic but definitely nonsinusoidal manner and the normal force increases beyond its stationary value past the stalling
angle of attack. The favorable effect of unsteadiness, specifically on the mean lift coefficient is obtained as a result of a cycle phenomenon of boundary-layer separation and reattachment on the upper surface near the leading edge.

Steven Ho et al (2002) showed that for large advance ratios (J>1), no vortex was observed and the flow was always attached. However, as the advance ratio was reduced below unity, the dynamic stall vortex appeared regardless of the chord size of the wing. For a span wise flexible wing the Lift coefficient decreases with decreases in advance ratio for J<1 the maximum $C_L$ obtained is around 0.5. On the other hand for a span wise rigid wing the $C_L$ increases with decrease in advance ratio and the maximum $C_L$ obtained was about 1.8.

2.2.2 Thrust Generation in Flapping Wing

Knoller and Betz provided the first theoretical explanation of thrust generation, that a flapping wing encounters an induced angle of attack, which cants the normal-force vector forward such that it includes both the lift and thrust components. Katzmayr provided the first experimental verification of the Knoller-Betz effect. Jones et al (1998) performed Water tunnel experiments and numerical simulations to investigate the generation and evaluation of wake structures behind flapping wings. The ability of a sinusoidaly plunging airfoil to produce thrust, known as Knoller - Betz or Katzmayr effect was investigated experimentally and numerically. Garric applied Theodorsen’s inviscid, incompressible, oscillatory, flat-plate theory to the determination of the thrust force and the formulation for pure plunge motion is,

$$C_t = \pi 4 k_G h^2 (F^2 + G^2)$$

(2.3)
where $F$ and $G$ are the real and imaginary parts of the Theodorsen lift deficiency function.

Jones and Platzer (1997), presented numerical procedures for the systematic computation of unsteady flow over moving airfoils or airfoil combinations, and these procedures are applied to the investigation of flapping-wing propulsion and power extraction. In the year 1999 the authors investigated flapping wing propulsion experimentally and numerically. They (2000) presented the flapping wing propulsion for micro air vehicle. They measured the thrust experimentally and compared with numerical predictions with variations in the flapping motion, aspect ratio and scale. The presented results indicate the necessities to understand better and ultimately to utilize the flow separation in the design of successful flapping wing MAVs.

Joseph C.S. Lai (1999) has presented about the characteristics of a plunging airfoil at zero free stream velocity. It is proved that at zero velocity, the lift generation is only due to wing flapping.

Gobalarathnam et al (2003) identified three types of interaction of the harmonically oscillating wing, used as a thrust generator, namely

- Optimal interaction of the oncoming vortices with those shed by the wing, resulting in the generation of still more powerful vortices in the wake in the form of a reverse Karman vortex street;
- Destructive interaction of oncoming vortices with those shed by the wing, resulting in the generation of weaker vortices in the wake in the form of the reverse Karman street;
- Formation of a vortex pair with vortices of opposite sign shed from the wing, this effect leads to the generation of a wide
wake composed of vortex pairs which are shed at an angle to the free stream.

2.2.3 Low Reynolds’s Number Study

Thomas J. Mueller and Stephen M. Batill (1982) has focused on the study of the leading edge separation bubble. A two dimensional NACA 66-018 section was chosen. This paper results the effect of the leading edge separation bubble as well as other separation and transition phenomena occurring on the airfoil in the low Reynolds number regime.

Brendel and Mueller (1987) investigated the characteristics of the transitional separation bubbles that form on the Wortmann FX63-137 airfoil. Pressure distributions, hot wire and laser velocimeter velocity profiles and flow visualization have been used for the study of transitional separation bubbles that occur at low-chord Reynolds number. The transition Reynolds number was found to increase with the increasing momentum-thickness Reynolds numbers at separation.

Wei Shyy et al (1999), presented the design of low Reynolds number airfoils such as the thickness, camber, and surface profiles. NACA 0012, CLARK-Y and S1223 airfoils are compared under various Reynolds number and angle of attack.

2.2.4 Stalling Characteristics

Isogai et al (1999) observed the numerical simulation of dynamic stall phenomena around an airfoil oscillating in a coupled mode, in which the pitching and heaving oscillations have some phase difference. It has been performed with a Navier-Stokes code.
Zoologist Ellington (1999) has presented the novel aerodynamics of insect flight, its applications to MAV’s. In this scaling, kinematics, control and stability aspect of insects were discussed and also he has discussed about LEV (Leading Edge Vortex) and dynamic stall effect of insects.


Peter G. Ifju et al (2002) documented the development and evaluation of an original flexible wing based micro air vehicle (MAV) technology that reduces adverse effects of gusty wind conditions and unsteady aerodynamics, exhibits desirable flight stability, and enhances structural durability.

2.3 COMPUTATIONAL SIMULATION FOR FLAPPING


Fritz et al (2004) introduced the unsteady vortex lattice method, which is used to model the oscillating, plunging, twisting, pitching and flapping of finite Aspect ratio wing. The model, which they created includes free-wake relaxation, vortex stretching and vortex dissipation effects.

Hall and Hall (1996) used a more sophisticated vortex lattice technique that, however, it was not involved in wake dynamics. The technique was used to evaluate the spanwise load distributions that corresponded with minimum induced power required for a given flight velocity, stroke amplitude and flapping frequency.
Basu and Hancock (1978), have developed a numerical method for the calculation of the pressure distribution, forces and moments on a two dimensional aerofoil undergoing an arbitrary unsteady motion in an inviscid incompressible flow.

Vernon J. Rossow et al (1977), present the theoretical study of the performance capabilities of a lift concept that utilizes a spanwise vortex over the upper surface of the wing. The analysis approximates the three-dimensional flow field with a two dimensional configuration that is mapped by conformal transformation into the flow about a circle.

Mark Drela and Michael B. Giles (1987) have presented the viscous/inviscid analysis method suitable for transonic and low Reynolds number airfoils. The applicability of the global Newton solution procedure to solve the entire coupled non-linear system of equations has also been shown.

Katz and Weihs (1978) presented a simple and rapid numerical technique for calculation of the time dependent growth and evaluation of wakes. The parameters influencing the roll up are examined and the ranges of reduced frequencies for which instabilities due to vortex wake of an oscillating airfoil, agglomerations of vortex element occurrence are determined.

Knut Streitlien et al (1996) investigated the problem of a heaving and pitching hydrofoil in an inflow that consists of a uniform velocity field and a staggered array of vortices. They found that the phase between foil motion and the arrival of inflow vortices is a critical parameter in the two-dimensional inviscid analysis. They also suggested from the observations of fast swimming species in the animal kingdom, the flapping hydrofoil can be a very effective means of propulsion.
Michael S. Vest et al (1996) have focused on the unsteady aerodynamic model of flapping wing. They examined the flow field around variable geometry bodies, with specific application to the unsteady flow associated with flapping wings. An unsteady, three-dimensional, incompressible, potential flow model was developed. The problem was formulated in an inertial reference frame as that the body moves through an otherwise quiescent fluid.

Ismoil H. Tuncer et al (1996) presented the thrust generation on a single flapping airfoil and a flapping/stationary airfoil combination in tandem. A multiblock Navier-Stokes solver was employed to study unsteady flow fields.

Ramji Kamoki et al (2000) have studied the biological flapping wing flight based on Strip theory, incorporating leading edge suction effect.

Ravi Ramamurti and William Sand Berg (2001) performed simulation of flow about flapping airfoils using finite element incompressible solver. Here the experimental verification was carried out for pitching, plunging and heaving motion.

Young and Lai (2004), simulated the wake of a two dimensional NACA 0012 airfoil. It was simulated with a compressible Reynolds number averaged Navier-Stokes flow solver with both fully laminar and fully turbulent flow assumptions. The results shows different wake structures due to different trailing edge flow behavior, but aerodynamic forces differ significantly only where leading edge separation is prominent. Trailing edge effects have a strong influence on the wake structures but only secondary effect on lift and thrust.
2.4 EXPERIMENTAL STUDIES ON MAVS

2.4.1 Flapping Mechanism Development

Weis-Fogh (1972) proposed a new circulating lift mechanism, called clap-and fling, to explain the high lift coefficients required for flight of very small chalcid wasps. This insect has small aspect ratio wings, which operate at the low Reynolds number of 100 and at fairly high-reduced frequency. The process of the wing motion of the circulating lift mechanism is called the Weis-Fogh mechanism. The $C_L$ obtained by the fling stage and translating phase is very large (3-6), specifically in the translating stages, and is almost independent of Reynolds number in the translating stage as well as in the fling stage.

Peter Krus (1997) proposed a mechanism that seems to be at least related to the way birds fly when they are gliding. It was demonstrated that how different dynamic behavior of flight could be applied on a geometrically unstable bird like configuration.

Robert C. Michelson and Steeve Reece (1998) developed an electromechanical multimode (flying/crawling) insect. An Entomopter based on a new development called Reciprocating Chemical Muscle (RCM), capable of generating autonomic wing beating from chemical energy source.

Metin Siffi (2000) developed the Piezo actuated four-bar mechanism with two flexible links for micro mechanical flying insect thorax.

Yan et al (2001) have designed and fabricated a 2 DOF resonant thorax structure for the Micromechanical Flying Insect (MFI). Miniature piezoelectric PZN-PT unimorph actuators were fabricated and used to drive a
four bar transmission mechanism and the current thorax utilizes two actuated four bars and a spherical joint to drive a rigid wing.

Mukherjee and Sanghi (2004) have described the design of a flapping mechanism used to realize the Weis Fogh mechanism of lift generation. They have also experimented with single drive design using concepts of motion synthesis by kinematics inversion technique followed by dynamic analysis.

2.4.2 Wing Development

De Laurier (1999) developed a human piloted engine powered ornithopter. He had used various analytical methods and wing construction techniques for the design and construction of the full-sized ornithopter.

Pornsin-Sirirak et al (1997), have developed the titanium alloy MEMS wing technology for MAV application. They also discussed the aerodynamic and flight-testing of the battery powered and capacitor powered ornithopters. In 1999, the authors presented the unsteady state aerodynamic performance results of various MEMS fabricated titanium alloy wing designs. They identified the importance of spanwise stiffness effect in generating the leading edge vortices. They have also introduced a novel stiffness-enhanced titanium alloy MEMS wing fabrication technique to increase the strength at the leading edge of the wing.

Yongsheng Lian et al (2003) have developed a nonlinear dynamic model for the coupled fluid and structure interaction. The effects of dynamic shape change of the membrane wing on the aerodynamic characteristics are presented. The approach is being employed to investigate the aerodynamic
characteristics as well as to facilitate shape design optimization of MAV wings.

Ashok Gopalarathnam et al (2003) presented the design philosophy for low Reynolds number airfoils that judiciously combined the tailoring of the airfoil pressure distribution using a transition ramp with the use of boundary layer trips.

Heathcote, Martin and Gursul (2004) have investigated the effect of aerofoil stiffness. Particle Image Velocimetry (PIV) and force measurements were taken for three aerofoils of relative bending stiffness 1:8:512. Vortex pairs for the rigid and flexible plates and alternating vortex streets for the very flexible plate were observed. There is strong effect plunge amplitude on the circulation of vortices, time averaged velocity and vortex spacing. The calculated momentum flux indicates larger influence of flexibility at small amplitudes. At high plunge frequencies, the thrust coefficient of the airfoil with immediate stiffness was great although the least stiff airfoil can generate larger thrust at low frequencies. They also suggested that the thrust, input power ratio was found to be greater for the flexible airfoils than for the rigid airfoil.

2.4.3  Aeroelasticity Study

De Laurier (1993) has formulated a method by which one can predict the flight performance of aeroelastically responding flapping wings. A flapping action is imposed on the elastic axis and the consequent aerodynamic and inertial-reaction loads give a steady state and time varying bending and twisting responses. A major assumption, in this is the strip theory modeling for each segment’s aerodynamic behavior.
2.4.4 Aerodynamic Characteristics Study

DeLaurier and Harris (1981) conducted the experimental study of flapping wing thrust. A wing was oscillated in a low speed wind tunnel. The driving apparatus produced nearly sinusoidal heaving with superimposed pitching of variable amplitude and phase angle. The average thrusting effort of the wing was measured and plotted in coefficient form against reduced frequency, with pitching amplitude and phase angle as a parameter. The author (1994) has also studied the physics of flapping-wing flight to gain insights on how animals fly and to assess the possibility of achieving this with a flapping–wing airplane (ornithopter). He also suggested that, successful sustained flight required the development of a comprehensive unsteady aerodynamic/aerostatic analysis complemented with wind tunnel experiments.

Bodapati Sathyanarayana and Sanford Davis (1978) described an investigation to find the range of reduced frequencies over which the classical Kutta-Joukowsky condition is valid and the nature of deviations beyond the range. Experimental investigations show that the differential pressure at the trailing edge approaches zero at lower reduced frequencies, whereas substantial deviations are reported at higher reduced frequencies.

Ismet Gursul et al (1992) studied the experimental results for a NACA 0012 airfoil at an angle of attack of 20 degree, which is higher than the static stall angle. The free stream velocity varied over a large range of amplitudes and frequencies. The velocity and lift measurement was carried out which results in an optimum reduced frequency, phase averaged lift coefficient can be one order of magnitude higher than the conventional values.
Lai et al (1999) gave water tunnel tests of a NACA 0012 airfoil that was oscillated sinusoidaly in plunge. The flowfield down stream of the airfoil was explored by dye flow visualization and a single component Laser Doppler Velocimetry (LDV) measurements.

Peter G. Ifju et al (2000) discussed the use of composite material in micro air vehicle. This work coordinates the flexible carbon composite material in the development of Black Widow MAVs. The conventional as well as the fastest ways of manufacturing MAV prototype model using carbon composite materials were discussed.

Antonia B. Kesel (2000) studied on aerodynamic characteristics of dragonfly wing sections compared with technical airfoils. The effects of cambered and flat airfoil of different shapes and their characteristics have been studied.

Broeren and Bragg (2001) presented the results of detailed investigations of the stalling characteristics of several airfoils that exhibited both low-frequency unsteadiness and large-scale three-dimensional structures. The airfoils were wind tunnel tested and the results showed that airfoils with trailing edge separations at and above maximum lift exhibited stall cell patterns.

David Munday and Jamey Jacob (2001) have presented the flow visualization over a NACA 4415 profile, which is not designed for low Reynolds number. The experiments were carried out at oscillating and fixed camber and suggested that an airfoil with oscillating camber will produce a higher lift coefficient than the same airfoil at any fixed camber setting.
Michael S Triantafyllou et al (2004) focused primarily on experimental studies on some of the mechanisms, which include 1) The formation of streets of vortices around and behind two and three-dimensional propulsive oscillating foils, 2) The formation of vertical structures around and behind two and three-dimensional foils used for maneuvering, hovering or fast starting; 3) The formation of leading edge vortices in flapping or transient conditions, 4) The interaction of foils with on coming, externally generated vorticity; multiple foils or foils operating near a body or wall.

2.5 RECENT DEVELOPMENTS IN MAVs

Wei Shyy, Mats Berg and Daniel Ljungqvist (1999), reviewed on flapping and flexible wings for biological and micro air vehicles. In this article they synthesis the various aspects related to low Reynolds number flight for both biological and man made flight vehicles.

Sanjay P. Sane and Michael H. Dickinson (2001) used a dynamically scaled mechanical model of the fruit fly *Drosophila melanogaster* to study how the changes in wing kinematics influence the production of unsteady aerodynamic forces in insect flight.

Woods et al (2001) described the power requirements for micro air vehicles, flying in the Reynolds number regime of \( \sim 10^5 \). Three flight modes have been researched: fixed wing, rotary wing and flapping wing. The energy and power requirements for the three flight modes have been calculated and an optimization procedure has been utilized to evaluate the most efficient flight mode and the configuration for a variety of specified missions.

Mihael Mesaric and Franc Kosel (2002) derived the analytical solution for calculation of unsteady air load on the airfoil with variable
camber for incompressible potential flow in order to avoid possibility of vibration and flutter suppression. The effects of the location of the maximum camber along the chord and the reduced frequency on the air load were also analyzed.

Kellogg et al (2002) presented the miniature autopilot system based on visual imaging technique for Micro Tactical Expandable air vehicle (MITE). Conventional autopilot sensors to allow the MITE to fly autonomously did this. This provides an overview of the MITE development including aerodynamic design considerations, electric propulsion and vision based autopilot research.

Robert J Fontana, Edward A Richley et al (2002) discussed the development of an extremely small, micro power, radar system utilizing Ultra Wide Band (UWB) technology, which addresses MAV mission requirements for collision avoidance and precision altimetry in support of autonomous vehicle operation. MAVCAS, a Micro Air Vehicle Collision Avoidance Sensor has been developed using a unique, spectrally confined ultra wideband waveform approach.

Rafal Zbikowski (2002) discussed the recent advances in the fluid dynamics of insect and MAV flight and considers theoretical analyses necessary for their future development.

Laura Guglielmini and Paolo Blondeaux (2003) determined the dynamics of the vortex structures generated by a foil in steady forward motion, plus a combination of harmonic heaving and pitching oscillations by means of the numerical solution of the vorticity equation.
Sanjay P. Sane (2003) has enabled the development of simple analytical and empirical models that allows calculating instantaneous forces on flapping insect wings more accurately than previous methods.

David L. Raney and Martin R. Waszak (2003) have contributed to an emerging body of multi-disciplinary knowledge in the area of biologically inspired micro-scale flight. The research activity seeks gain and applies an understanding natural flier in the size range of the micro aerial vehicle class.

Kevin D. Jones et al (2003) presented the experimental and computational results for two configurations, which benefited from the flow separation control. Both configurations operate at low Reynolds numbers in the order of $10^4$, characterized by laminar flow often where separation is unavoidable.

### 2.6 NEED FOR THE PRESENT STUDY

Sunada, Yasuda et al (2002) measured the hydrodynamic characteristics of 20 wings of different airfoil shape at $Re = 4 \times 10^3$. The wings have the aspect ratio of 7.25. Hydrodynamic characteristics of a wing with a rectangular airfoil can be improved by either a camber of 5%, a sharp leading edge or proper corrugation. The study shows that the thinner wing has better hydrodynamic characteristics, however a thinner wing has lower rigidity. When the thinner wing cannot support the pressure because of low rigidity, corrugation is effective.

Hiroto Tanaka et al (2002) developed a very small and light Butterfly Type Ornithopter (BTO). The flights were recorded with a high speed video camera and the longitudinal motion of the BTO was analyzed and
found that the cyclical change of the angle of attack produced total upward aerodynamic force.

Warrick, Bundle and Dial (2002) examined the utility and units of fixed wing models of maneuvering flight, and suggest new directions investigations into maneuvering flight should take given recent revelations. In addition they are discussed the aerodynamic mechanisms birds use to maintain stable flight. And also provide preliminary data on the function and importance of the cervical musculoskeletal mechanisms birds use to isolate their heads from the often violent kinetic energy of flapping and maneuvering flight.

Jia-chi Wu and Zoran Popovic (2003) described the physics-based method for synthesis of bird flight animations. They described the algorithms for dynamic simulation of a bird following the given flight trajectory. They also described the methods to compute a realistic set of wing beats that enables a bird to follow the specified trajectory. They described an offline method for bird flight synthesis.

David R Raney and Eric C Slominski (2004) studied mechanization and control concepts with application to resonant MAV’s. Structural approaches, mechanical design, sensing and wing beat control concepts inspired by hummingbirds, bats and insects are examined.

Kirill V. Rozhdestvensky and Vladimir A. Ryzhov (2003) have given the survey to review research and development results of flapping wing propulsors and of vehicles equipped with them. Also, the physical and the design factors are discussed, which affect the aerohydrodynamic characteristics of flapping wings and therefore have to be accounted for in the modern mathematical models.
Beerender Singh et al (2004) addressed the aerodynamics of insect based, biomimetic, and flapping wings in hover. Experiments have been carried out and shown. The lift and drag coefficients on flapping wings are higher because of the leading edge vortex. The results are based in flapping stroke angle of $80^\circ$ and each wing was tested at two pitch angels of $30^\circ$ and $45^\circ$ during upstroke and down stroke respectively. Preliminary flow visualization tests were conducted on the two wings at a wing pitch angle of $45^\circ$.

In the present study the total development of flapping wing MAV that includes, flapping mechanism development, wing planform development, integration, aerodynamic characteristics study both by computational and experimental was considered. The tests were carried with various flapping mechanisms like movable hinge, fixed hinge, rack-gear and miniaturized rack-gear mechanisms with different wing planforms. Here the various mechanism parameters like flap angle, flapping frequency and aerodynamic parameters like AR, wing planform shape, chord and span wise cambered effect were considered in the experiment. The flight test also been conducted.