LITERATURE REVIEW OF THE AERODYNAMICS OF FLAPPING FLIGHT IN MICRO AIR VEHICLE APPLICATIONS

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Literature Review of the Aerodynamics of Flapping Flight in Micro Air Vehicle Applications

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MASTER OF SCIENCE

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ABSTRACT

Biological flapping wing flyers achieve flight maneuverability and efficiency in low speed flight environments that has not been replicated by man-made flyers. Micro Air Vehicle (MAV) design goals are to develop flyers that maintain flight in environments that biological flyers excel in which includes low speeds, hovering, and urban settings. This flight is characterized by flow phenomena that are not well understood such as: flow separation and vortical flow. The goal of this study is to perform a literature review about the aerodynamics of flapping flight and discuss the application to MAV design. The study will evaluate the design initiatives of MAV. Experimental and computational test methods are reviewed. Low Reynolds number aerodynamics are studied. The effects of airfoil aeroelasticity and geometry are discussed. Then, the application of the aerodynamics to flapping motions are reviewed. Finally, operational MAV designs are studied and recommendations are made to further advance the state of the art.

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1. INTRODUCTION

Birds and insects utilize flapping wing motions to achieve flight maneuverability and efficiency in low speed flight environments that has not been fully understood or replicated by man-made flyers. The goal of Micro Air Vehicles is to develop flyers similar in size and appearance to biological flyers that can fly in the same flight environments that biological flyers excel in. This flight environment possesses complex aerodynamics characterized by low speed flight (low Reynolds number), maintained hovering flight, urban environments, indoors flight, etc. The low Reynolds number flight environment is characterized by complex flow phenomena such as: viscous flow, transition from laminar flow to turbulence, flow separation, vortical flow, etc.

These flow phenomena are rarely experienced in high Reynolds number conventional fixed wing flight and have not been extensively studied. Due to the complexities of flapping flight aerodynamics, the aerodynamics are not well understood. The purpose of this study is to perform a literature review of the aerodynamics of flapping flight for MAV applications, then make recommendations on the future direction to advance the state of the art.

The purpose of flapping MAVs and the performance goals will be outlined along with other design considerations. The complexities of these design considerations will be briefly introduced to outline the direction and development of the state of the art. Much of the design considerations were derived from the performance capabilities of biological flapping flyers. These characteristics will be reviewed to form a baseline for flapping flight studies. Fixed wing and rotary wing (helicopter) flight modes have been in use for a long time and are more understood than flapping wing flight. They can also be designed to meet MAV design goals. Fixed wing, rotary wing, and flapping wing flight will be compared to outline the advantages and disadvantages of flapping wing flight that justify the value of flapping wing MAVs.

Testing techniques will be briefly reviewed to outline the capabilities of experimental and simulation testing techniques to characterize the aerodynamics of flapping flight. Multiple experimental and simulation techniques will be reviewed to outline the ability of the current state of the art to accurately characterize MAV flapping flight, as well as realize opportunities for improvement towards fully understanding flapping flight.

Multiple design options need to be chosen to achieve the flight performance goals for a specific MAV design. The primary design options that are specific to aerodynamic performance are wing geometry, wing flexibility, and flapping parameters. In order to determine which flapping flight parameters and motions to use in MAV design, the low Reynolds number flow phenomena must first be understood to determine their effect on the aerodynamic performance. Several significant low Reynolds number flow phenomena are reviewed to determine the aerodynamic effect. Next the effect of geometry and wing flexibility is briefly reviewed to understand their effect on the aerodynamic performance of the MAV. Once the aerodynamic phenomena are understood, flapping motions can be characterized and designed to manipulate the aerodynamic phenomena to achieve flight goals. The performance goals of MAVs vary dependent on their application. Multiple flight modes are reviewed to outline the performance requirements of different flight modes and flapping parameters to achieve the desired performance.

With the overwhelming number of variables and performance goals of each specific MAV application, optimization methods are needed to minimize computational and experimental cost. Optimization techniques that have been developed for MAV are reviewed to determine the state of the art and realize opportunities to advance the state of the art.

Finally, fully operational MAV designs that have been developed are reviewed. This leads to a final review of the current state of the art of understanding flapping flight aerodynamics for MAV applications along with recommendations for future study to further understand flapping flight aerodynamics and their application to MAV design.

1.1. MAV Design Considerations

The overall goal of MAV design as outlined by Defense Advanced Research Projects Agency (DARPA) is to create flyers that can fly in low Reynolds number flight environments and are comparable in size to biological flyers to be inconspicuous and able to maintain controlled flight in small spaces. MAVs primary use would be reconnaissance, but also carry measurement or sensory equipment. Currently in many military applications Unmanned Air Vehicles (UAV) are large, fixed wing aircraft (example in Figure 1 below) that cannot maintain flight in low Reynolds number flight environments [1-2].

Figure 1: Fixed-wing Reconnaissance UAV [3]

In 1997, DARPA set MAV design initiatives that it considered to be technologically feasible and would be a size comparable to biological flyers. More recently DARPA set design initiatives for Nano Air Vehicles (NAV), which are more reflective of current state of the art. The primary design constraints are shown in the Table 1 below [1-2].

Table 1: MAV, NAV Constraints [1-2]

Constraint	MAV	NAV
Max Length	15 cm	7.5 cm
Velocity	10 m/s	5-10 m/s
Max Mass	50 g	10 g
Min Flight Time	20 min	20 min
Hover Capable	No	Yes

Overall, the NAV has tighter restrictions to be closer to biological flight. The primary difference is that the NAV needs to be capable of hovering. This eliminates fixed wing flyers because they need forward flight to produce lift. Most studies referenced in this review consider MAV design constraints because of NAV's recent release.

These design constraints were chosen to be comparable to biological flyers, so biological flyers will be baselined for designing MAVs. Biological flyers are small in size and capable of maintaining highly maneuverable, quiet, and efficient flight in low Reynolds number flow environments. Nature has provided a blueprint of MAV design that the scientific community has not been able to replicate. In order to achieve comparable flight characteristics of biological flyers are studied to integrate into the design of MAVs.

1.2. Flap, Fixed Wing, and Rotary Flight Comparison

There are three primary types of MAV flight designs that have been extensively studied. Fixed wing flight, rotary flight, and flapping flight, shown in Figure 2 below.

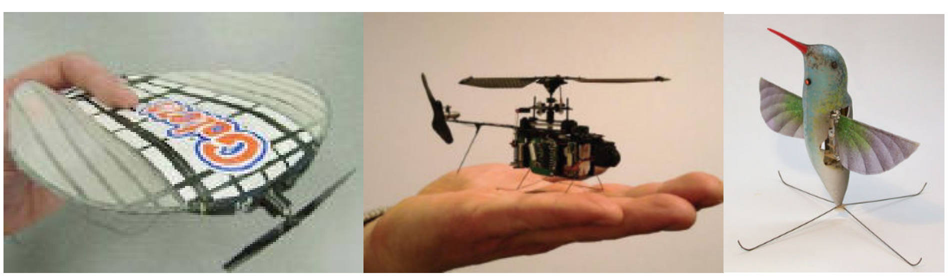

Figure 2: Fixed, Rotary, and Flapping Wing MAVs [4-6]

Fixed wing flight is similar to conventional fixed wing planes that use a propulsion system to maintain flight. Rotary wing flight is similar to helicopter flight, except at a smaller scale. Rotary wing flight achieves flight through the rotation of the airfoils about a vertical axis. Flapping flight mimics biological flight to achieve flight through the flapping motion of the wings. In Table 2 below, these three MAV designs are compared to evaluate the advantages and disadvantages of each flight type. Green is the best performance, yellow is moderate performance, and red is poor performance.

Table 2: Fixed, Rotary, and Flapping Comparison

Type	Hover	Complexity	Agility	Efficiency	Noticable
Fixed					
Rotary					
Flapping					

As shown in Table 2 fixed wing flyers are not capable of hovering. This is because fixed wing flyers use forward flight to generate lift. Flapping wing flyers possess superior agility and efficiency when compared to both rotary and fixed wing flyers. Also, flapping wings can be designed to move and look inconspicuous like a biological flyer. The main problem with flapping flyers is that the flapping flight is very complex and not fully understood. Only a few fully operational flapping MAVs have been created. Rotary flyers have been used for decades and have established computational models. Flapping flyers have the potential for superior maneuverability and efficiency after the aerodynamics are fully understood [2, 7-12].

2. TESTING TECHNIQUES

The desire to mimicking biological flyers and creating flapping flyers has been around for centuries. But until recently the experimental or computational capabilities did not exist to effectively evaluate the aerodynamics to apply them to MAV design. In the last 25 years, advancements in experimental and computational techniques have made MAV design feasible. Along with that, advancements in materials science, control systems, and lightweight power sources have also made MAV design possible. The following early studies formed the framework for MAV flight aerodynamics.

2.1. Early Studies

Mankind has tried to understand and mimic biological flapping flyers for centuries, from Icarus’s wings in Greek mythology to Da Vinci’s flying machine shown in Figure 3. All of these attempts did not accomplish flapping flight or vastly expanding the understanding of it.

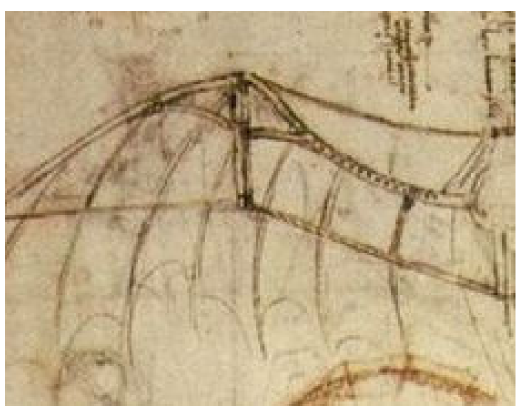

Figure 3: Da Vinci's Flying Machine [13]

In the 1900s, scientists began to study individual flapping motions to characterize their aerodynamic properties. In 1912, Knoller-Betz was able to determine that thrust was produced by a plunging flapping motion [14-15]. In the 1930s, Von Karman and Burgers discovered that the Reverse Karman Vortex pattern off of the trailing edge was indicative of the flapping motion producing thrust [16-17].

This progress starting at the beginning of the century set the foundation for the rapid expansion of flapping flight studies and resulting expansion of the understanding of the aerodynamics. In the 1990s, experimental techniques and computational solvers increased the accuracy of flapping flight studies so that the aerodynamics could be reasonably understood. Also, advances in material science, control systems, and miniaturized power sources have been developed to the point that a fully operational MAV was conceivable [1].

2.2. Experimental Techniques

In order to understand the aerodynamics of flapping wing MAVs, accurate experimental and simulation methods are needed. Due to the small size of MAVs and their complex flow aerodynamics, it is difficult to measure the aerodynamic forces and capture the flow patterns, but accurate prediction of the aerodynamics is critical to evaluate flow characteristics and eventually apply the aerodynamics to MAV design. There is no faultless simulation method that can fully predict the aerodynamics, so experimental data is needed to validate simulation methods. This section will review various test tunnel types and measurement mechanisms used to evaluate MAV flight [70].

2.2.1. Test Area Types

The low Reynolds number environmental conditions need to be replicated in the testing area. Even minimal air circulation in the test area can affect the flow quality because common air circulation is often the same order of magnitude as the low speed flow. Wind and water tunnels are used in low Reynolds number flows, and still air rooms are often used for hovering conditions. Each of these flow environments has advantages and disadvantages. The optimal flow environment varies dependent on motion, flow conditions, geometry, structure, etc. of the MAV application.

2.2.1.1. Water Tunnels

Water tunnels are often used instead of wind tunnels to help visualize vortical flow at low Reynolds number flow. Due to the higher density of the fluid, the fluid does not have to flow as fast to achieve the proper Reynolds number condition. Also, dye can be injected into the water and the vortical flow can be clearly seen and measured as seen in Figure 4 below [18-20]

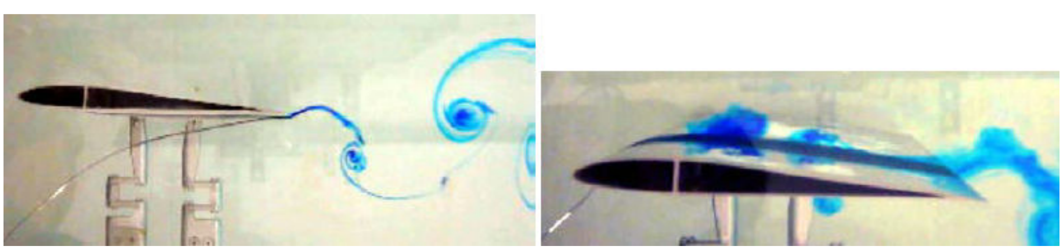

Figure 4: AFRL Water Tunnel [18]

2.2.1.2. Wind Tunnels

Wind tunnels are commonly used to produce low Reynolds number flows and isolate the environment from other flow in the room. Smoke particles can be inserted into the air to visualize and measure the flow conditions. Many times wind tunnels specifically designed for low Reynolds number flow are needed to obtain accurate flow at such low speeds. Most wind tunnels are designed to test high Reynolds number conventional flight. Wind tunnels are more accurate than water tunnels when the airfoil is not rigid. The inertial deformation of the airfoil is not the same in air and water during flapping. Figure 5 shows a schematic of a wind tunnel from the Technical University of Braunschweig [18, 21].

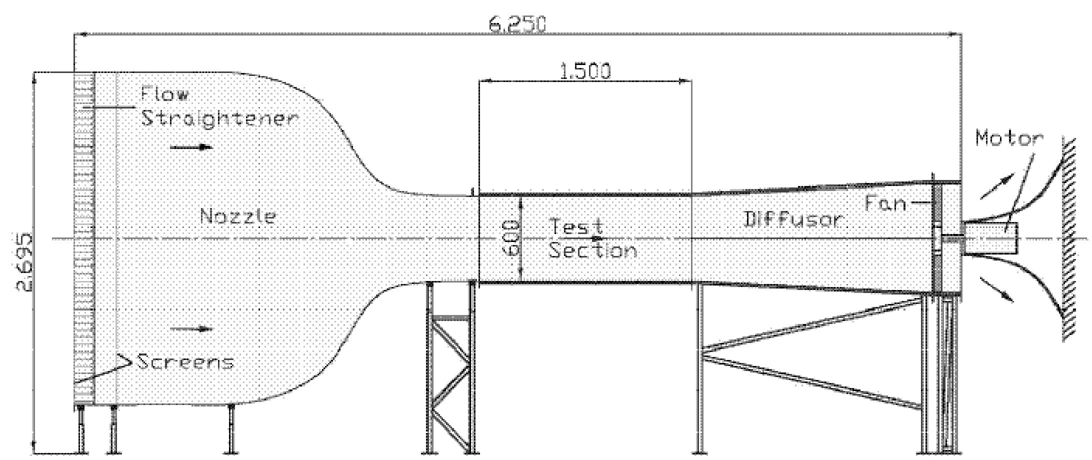

Figure 5: Wind Tunnel Schematic [21]

2.2.1.3. Open Air (No velocity)

Open air, still rooms are used primarily for hovering applications. The still air will simulate flow conditions if the MAV is maintaining hovering flight. It is difficult to visualize and measure flow in these applications since the vortical flow from previous flapping cycles is often captured in following cycles. Also, smoke particles cannot be inserted upstream and blown downstream between flapping cycles.

2.2.2. Flow Visualization Methods

In order to capture all of the consequential vortical flows flow visualization methods must be used to measure the flow and determine the local flow velocities of the test area. Vortical, multi-directional flow patterns make it so tools like pitot tubes or anemometers are not able to obtain close enough access to the flow area without obstructing the flow.

2.2.2.1. High Performance Cameras

In recent years the development of high speed cameras in general has greatly increased experiments' capability to track particles in the air as the air flows across a flapping wing.

2.2.2.2. Particle Image Velocimetry

Particle Image Velocimetry (PIV) is commonly used to measure the aerodynamics of flapping flight flow due to its high accuracy and is an optical measurement method. Figure 6 shows comparison of the vortical flow behind an airfoil with accurate PIV experiments and 2D simulations. The red and blue vortical patterns in each are nearly identical in size and location.

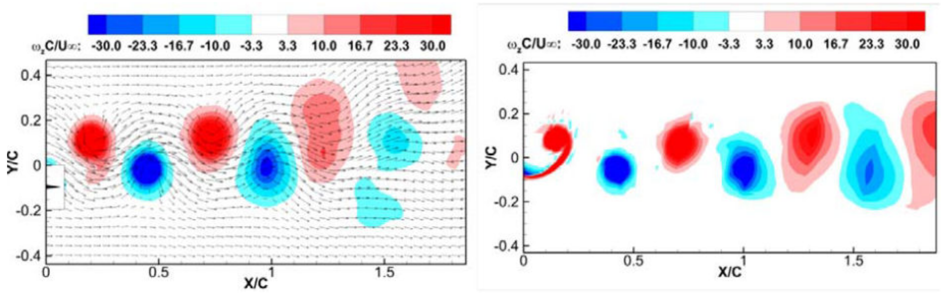

Figure 6: PIV (Left) and Experimental (Right) Flow Comparison [10]

The measurements can be taken without the instrumentation affecting the flow. PIV begins with releasing dye or smoke into the test area. Then a laser that rapidly pulses through a series of mirrors and prisms creates a laser sheet about the area of interest. This laser sheet acts as a canvas for a high powered, rapid shutter camera to capture the reflection of the dye or smoke particles. The camera and laser pulse quickly in unison to track the motion of the particles. The velocity of the flow field can be determined from this particle motion. The system is illustrated in the Figure 7 below [10].

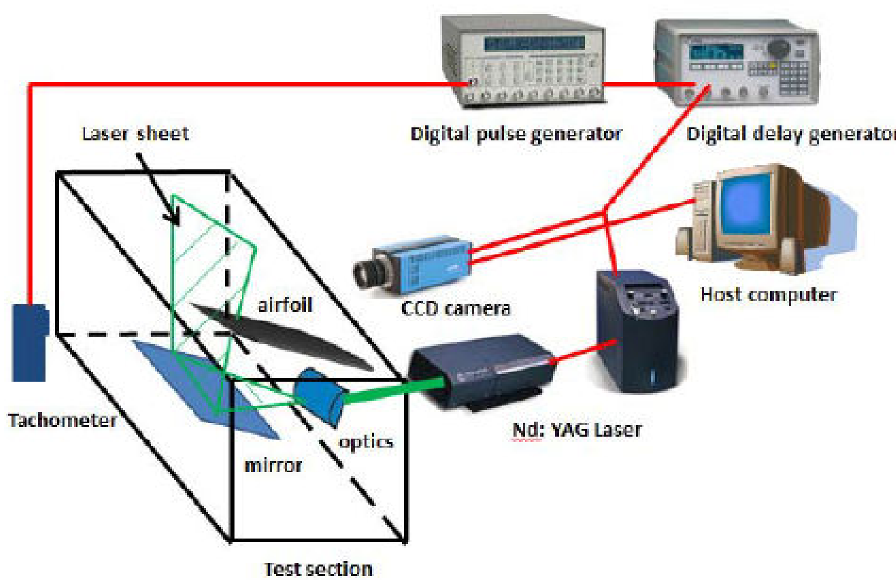

Figure 7: PIV System [10]

2.2.2.3. Flow Visualization: Dye, Smoke Injection

Dye and smoke injection are usually used for other visualization methods to measure the flow with cameras, but it is helpful to show vortical flow patterns that are visible with the naked eye without having to process the images with software. In Figure 4 blue dye is inserted into the flow at the top of the airfoil to clearly show the flow circulation off of the trailing edge of the airfoil [18].

2.2.3. Loading Measurements

The loading conditions on the airfoil determine if the flapping motion produces lift, thrust, drag, etc. Evaluating the loading conditions accurately is critical.

2.2.3.1. Pitot Tube

Pitot tubes measure the pressure differential between dynamic and static pressure. From these pressures the loading conditions of that exact local area can be determined. However pitot tubes are not useful in evaluating loading conditions of the entire airfoil due to the pitot obstructing the multi-directional flow around the airfoil [22].

2.2.3.2. Load Cells / Strain Gauges

Load cells and strain gauges are small and thin and can be adhered to the surface of the airfoil. Their small size and low profile minimizes effect on the flow when compared to a pitot tube, but it does still affect the flow. Like pitot tubes, load cells and strain gauges only evaluate the loading conditions at their local area, not the entire test area [23-24].

2.2.3.3. PIV

Using pressure equations, the loading conditions can be determined from the velocity measurements of PIV. This method is simple, and the loading conditions of the entire test area can be determined. One disadvantage is that if the PIV measurements are inaccurate, the loading measurements will be inaccurate too.

2.3. Computational Techniques

In order to understand the aerodynamics of flapping wing MAVs accurate evaluation methods are needed. Due to the small size of MAVs and their complex low Reynolds number flow aerodynamics, it is far more difficult to simulate the aerodynamics than conventional fixed wing aircraft at high Reynolds number flows. Viscous flow, unsteady flow, transition to turbulence, and vortical structures are some of the aerodynamics that must be accurately predicted to understand the flow. Small changes in these computation parameters can have a significant effect on the overall flow. The complex aerodynamics compound the computational cost requirements needed to evaluate the flow. Accurate, but cost effective computational techniques are required to evaluate the flow. This section reviews the progress of understanding simulation parameters and computational techniques to accurately simulate MAV aerodynamics [25].

2.3.1. Simulation Parameters

There are various flow characteristics that must be accounted for in the simulation parameters. Many of these parameters add a great deal of complexity and computational cost to the flow. The effect of these parameters needs to be determined in order to make efficient use of computational cost and time.

2.3.1.1. Incompressible Flow

All fluids are compressible at high enough pressures. Since low Reynolds number flow is so slow for MAV applications, the air compression is negligible [26].

2.3.1.2. Unsteady Flow

Unsteady flow means that the flow is not constant over time. Unsteady flow is common in flapping flight aerodynamics. The aerodynamics of a flapping cycle can overlap the aerodynamics of the previous cycle. Often small disturbances in the aerodynamics can cause a significant change in overall aerodynamic performance [27].

2.3.1.3. Viscous/Inviscid

Viscosity is the tendency of a fluid to resist deformation due to bonding within the fluid. In conventional, fixed wing flight, this parameter is usually negligible. However, at low Reynolds number flow, the viscous forces have a more noticeable effect on the aerodynamics. Adding the viscous parameter does add a considerable amount of computational cost [21].

2.3.1.4. Laminar, Transitional, and Turbulent Flow

Laminar, transitional, and turbulent flow is experienced during most MAV flapping motions. The accurate prediction of these flows is critical to the accuracy of the MAV. Transition and turbulence can be utilized to improve the performance of the airfoil or it can be detrimental. The accurate understanding of this flow can be the difference between creating lift or drag. Inaccurate prediction of the transition point can lead to the misinterpretation if the flow reattaches to the airfoil after onset of turbulence [18, 26].

2.3.2. Navier Stokes Equations

The Navier Stokes equations are the primary fundamental equations of fluid flow. The computations are not a perfect representation of flow, but are considered accurate. Each simulation parameter listed above can be accounted for in these equations. The primary equation for MAV applications is shown below. Figure 8 shows an explanation of the variables. The inertia is a combination made up of the change in acceleration over time plus the change of acceleration in all three dimensions. The inertia is equal to the summation of the pressure gradient over time, the dynamic viscosity, and external body forces. The equation expands into many more terms when all three dimensions are written out [26].

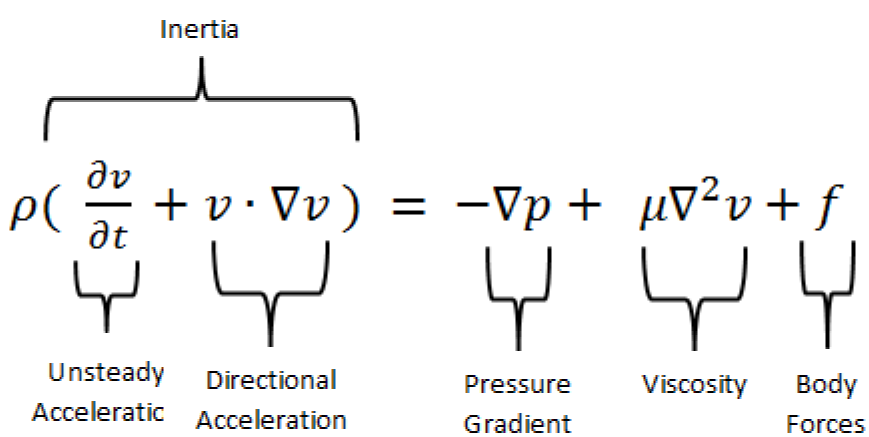

Figure 8: Navier Stokes Equations [28]

The flow can be assumed to be 2D, or all three dimensions can be accounted for. Each additional parameter considered adds computational cost to the simulations. The proper balance of accuracy vs computational cost must be determined for efficient design methodologies.

Considering flow in only two dimensions assists in further isolating a specific flight motions or condition and reduces computational cost. Until recent advancement in computational power, most computations were done in 2D due to the complexity. Before final design all three dimensions need to be considered, but the isolation of variables helps in the initial characterization of aerodynamics. 3D flow requires a greater computational cost, but allows for aerodynamics of the entire test area to be accounted for. Due to their small size and slow flight speed, spanwise flow is common in MAV flow, thus 3D simulations are needed. The proper manipulation of spanwise flow and geometry can improve MAV performance.

2.3.3. Fluid Flow Solvers

Fluid flow solvers simulate the aerodynamics the flapping motion. Fluid flow solvers must be able to account for all aerodynamic parameters that are required. The solvers accurately predict the aerodynamics of the flapping MAV environment such as: vortical flow, transition to turbulent flow, turbulent flow, flow separation, and flow reattachment. The computational cost of the solver is based on the complexity of the flapping MAV as well as the fidelity of the solver. The proper balance of computational cost and accuracy must be determined.

2.3.3.1. Reynolds Averaged Navier Stokes (RANS) Solver Simulation Method

Reynolds Average Navier Stokes (RANS) solver is a high fidelity solver capable of simulating low Reynolds number flow. It has been used for flapping MAVs, fixed winged, helicopter blades, and wind turbine computations. RANS has high computational cost due to the high fidelity. The need for this high fidelity may or may not be justified based on the specific MAV application [25, 29].

2.3.3.2. Large Eddy Solver (LES) Simulation Method

Large Eddy Solver (LES) is a high fidelity solver capable of simulating low Reynolds number flow. LES has high computational cost due to high fidelity. LES is capable of capturing small vortical flow phenomena that can lead to more impactful flow further along in the flapping motion [30, 18].

2.3.3.3. Direct Numerical Simulation (DNS) Method

Direct Numerical Simulation method is a high fidelity solver capable of simulating low Reynolds number flow. DNS has high computational cost due to high fidelity. DNS is capable of capturing small vortical flow phenomena that can lead to more impactful flow further along in the flapping motion [30].

2.3.4. Fluid Solid Interface for Flexible Airfoils

In flexible airfoil applications, the flapping motion of the MAV causes deformation of the flexible airfoil, which affects the aerodynamics around the wing. The resulting affected aerodynamics then further deforms the airfoil shape. This pattern is ongoing over the entire flapping flight of the MAV. The fluid flow solver and the Finite Element Analysis (FEA) solver must be coupled at each time step to capture the effect each has on the other.

This process is called Fluid Solid Interface (FSI). The computational cost of coupling the already expensive fluid flow solver with the FEA solver is high. Until recent years computational solvers were not capable of running the simulations at a feasible computational cost.

Numerous FSI techniques and solvers exist in varying fidelity and computational cost. Specifically, the University of Michigan computational simulation framework methods have many FSI variations specifically designed for different flapping, flexible wing MAV applications. The University of Michigan solvers are not commercial solvers applied to MAV applications, but specifically designed for MAV simulations. These methods have a high computational cost to run, but are highly accurate, 3D, and have had extensive development and validation testing [23, 31-32].

3. LOW REYNOLDS FLAPPING FLIGHT AERODYNAMICS

In order to design operational MAVs the aerodynamics of low Reynolds number flapping flight aerodynamics must be understood. Numerous flow phenomena are encountered in this flow such as, vortical flow, transition to turbulence, wake capturing, gusting, etc. Each of these flow phenomena's aerodynamic effects must be individually understood in order to apply to MAV design. Often the experiments and simulations are designed to eliminate variables and isolate an individual phenomenon. The aerodynamics can then be controlled via MAV geometry, airfoil flexibility, flapping motions, flight speed, and intended flight environment in order to achieve the desired MAV flight performance [33-34].

3.1. Characteristics of MAV Flow

MAV flow environments are characterized by many complex, unsteady flow phenomena not seen in conventional flight and not well understood. Low flight speeds and hovering flapping creates flight complex vortical aerodynamics. These vortical aerodynamics interact with the airfoil and affect performance. The low flight speed allows for vortical flow patterns to form while on the airfoil and remain in contact with the airfoil for a longer duration. Due to the small size of MAVS, their wings often have a low aspect ratio (wing span/wing chamber) which promotes spanwise vortical flow. Urban and indoor environments create multi-directional, turbulent gusting and aerodynamic flow complications. The velocities of these gusts are many times the same order of magnitude or greater than the flight velocities of the MAV. Conventional aircraft fixed wings create uniform flow conditions that achieve aerodynamic conditions closer to steady state. The high aspect ratio wings make the effect of spanwise flow minimal. Conventional aircraft flies at high Reynolds number and quickly disperses the vortical flow phenomena off the airfoil. The high Reynolds flow also reduces the effect of gusting because the gust velocities are inconsequential in comparison to the flight velocity. The flow environments are above most flow obstructions, which minimize gusting. Figure 9 below illustrates steady, conventional aerodynamics versus unsteady, complex aerodynamics. The aerodynamics on the left possess mostly attached airflow to the airfoil with little spanwise flow. The aerodynamics on the right are complex, with massive separation and multiple detached vortex patterns. These aerodynamics are common in MAV flow [35-40].

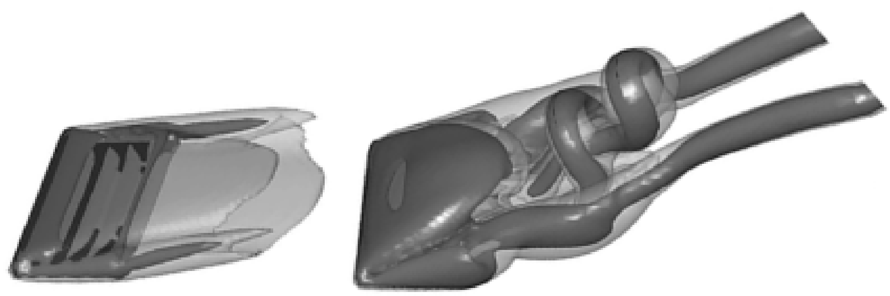

Figure 9: Conventional Aerodynamics vs Complex Aerodynamics [37]

3.2. Vortical Flow

Vortical flow is a primary controller of the aerodynamic performance of flapping MAVs. Vortical flow is a circulating segment of the flow about a concentric point created by flow around an object, aerodynamic stresses, or inertial forces of the flapping motion as shown in Figure 10. Vorticies are caused by objects or stressors in multiple locations along the airfoil, and vary by size, intensity, shape, etc. Circulation is the strength of the vortical flow. The interaction of the vorticies with the airfoil and other flow aerodynamics can improve or decrease flight performance and must be understood and controlled in order to achieve optimal MAV performance [26].

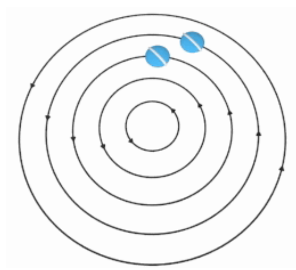

Figure 10: Vortical Flow Motion [41]

3.3. Adverse Pressure Gradient

As air passes over the leading edge of the airfoil the pressure increases creating an adverse pressure gradient. Adverse pressure gradients are common in most airfoils. The adverse pressure gradient has a significant effect on the aerodynamics slowing the fluid flow down creating a velocity gradient from airfoil to the edge of the boundary layer, as seen in Figure 11 below [26].

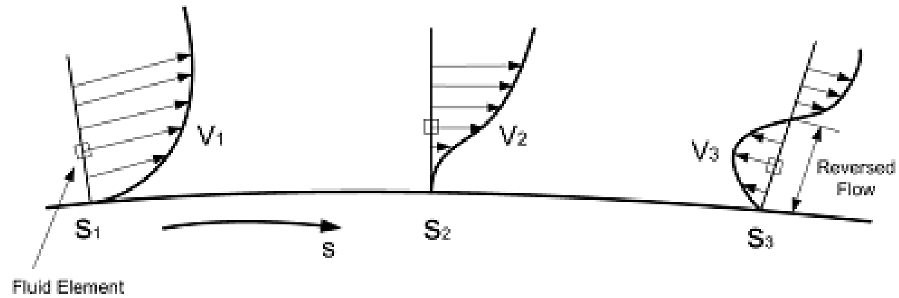

Figure 11: Adverse Pressure Gradient [42]

3.4. Viscous Flow

Viscosity is the resistance of a fluid to free movement due to friction forces with a solid object or within the fluid. Viscous flow creates a boundary layer around the airfoil shown in Figure 12 [26].

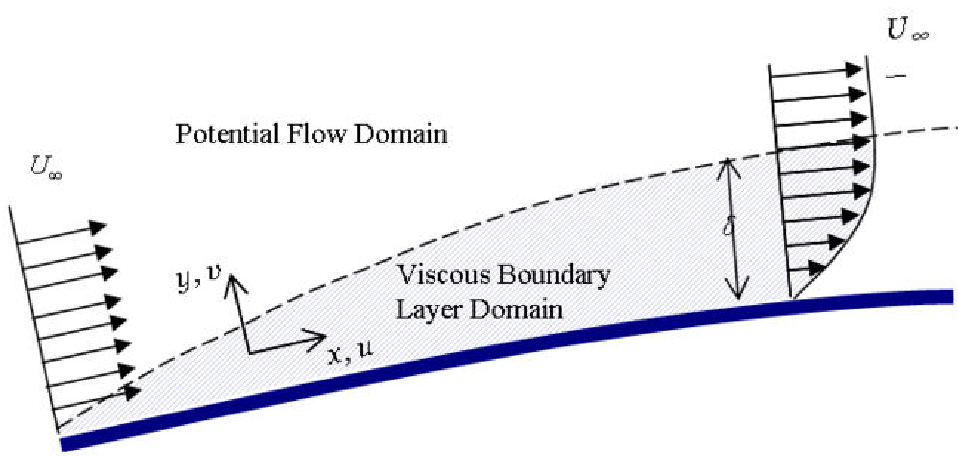

Figure 12: Boundary Layer [43]

Outside the boundary layer, the viscous forces are inconsequential. Much of conventional flight can be considered inviscid due to high Reynolds number flow far larger than the velocity reduction caused by viscous forces. Low Reynolds number flight is closer in magnitude to the viscous forces, thus the boundary layer is much wider and affects a larger percentage of the flow. For simulation studies, when the fluid flow is fully attached, usually at low angles of attack, the fluid flow is largely inviscid. However, when flow separation occurs, usually at high angles of attack, viscous flow needs to be included [26].

3.5. Flow Separation

Flow separation occurs when on the top of the airfoil adverse pressure gradients along with viscous forces slow the fluid flow to a standstill and reverse flow, causing the flow to separate from the airfoil as shown in the Figure 13. The low Reynold's number of MAV flight possesses lower inertial forces, thus the adverse pressure gradient and viscous forces create separation quicker than in conventional flight. Following flow separation, the separated flow will transition from laminar to turbulent flow.

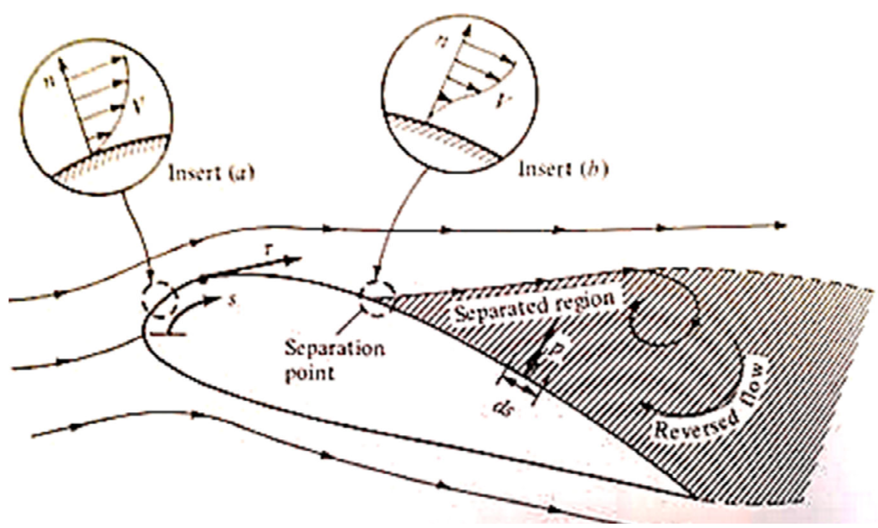

Figure 13: Flow separation [26]

The separated flow creates a low pressure region above the airfoil, which increases lift. The low pressure region also creates pressure drag when there is flow separation at the trailing edge. When the flow is fully attached the entire length of the airfoil the pressure at the trailing edge approximately equals that of the leading edge, but when the flow separates at the trailing edge the low pressure region at the trailing edge is less than the leading edge. Flow separation can be especially detrimental to lift and thrust if stalling occurs. When the boundary layer separates from nearly the entire top of the airfoil, it results in a significant dip in lift and thrust. Figure 14 shows the lift versus the angle of attack and the corresponding streamlines of the flow as the angle of attack increases [26].

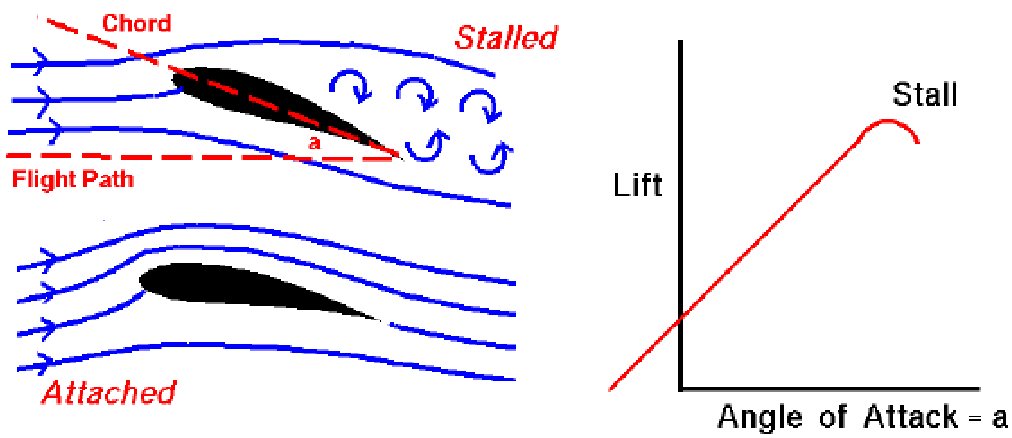

Figure 14: Stalling [44]

The coefficient of lift increases until the max lift is achieved, after which stall occurs resulting in flow separation and a significant dip in lift [26].

If the separation bubble reattaches to the airfoil it creates a laminar separation bubble (LSB). Also, vorticies can detach from the airfoil surface, but still follow the surface of the airfoil. This reduces the drag by removing separation at the trailing edge while still creating a low pressure region to increase lift. Utilization of flow separation is essential in MAV flapping flight, especially in hovering situations where maximum lift is needed without forward movement to create lift. However for forward flight or cruising flapping motions, the lift can be created by the forward flight, while pressure drag needs to be minimized by maintaining flow attachment and reattachment [26].

For simulations, before flow separation, the flow is largely inviscid, but when flow separation occurs, the flow is dominated by viscous flow. Thus viscous flow needs to be included in most MAV flow calculations. In several flapping MAV studies, flow separation created pressure drag and reduced the propulsive efficiency. During the flapping, the flow usually quickly transitions from laminar to turbulent flow which causes further unsteadiness to the flapping aerodynamics. Flow separation can be controlled by flapping kinematics, flexible airfoils, geometry, and flight conditions [1, 45-49].

The MAV flapping motions often involve high angles of attack which creates significant flow separation, especially in hovering scenarios where flow separation is utilized to obtain the needed maximum lift. The MAV flow environment experiences extensive gusting which can create flow separation, and rupture attached vortical flow into massive separation quickly. The flow is difficult to measure, simulate, and visualize, but accurate prediction of the aerodynamics of the flow separation is required for proper control of the MAV to maintain flight in the unsteady, turbulent, environment MAVs must fly in.

3.6. Transition From Laminar to Turbulent Flow

Transition from laminar flow to turbulent flow is unavoidable in flapping flight. Transition follows quickly after flow separation. The transition from smooth laminar flow to turbulent flow drastically affects the aerodynamics. The aerodynamics of laminar flow are smooth, simple, and regular while the aerodynamics of turbulent flow are complex, random, expand into a wider aerodynamic area, and are difficult to understand. Figure 15 below shows the transition from laminar to turbulent flow [26, 49].

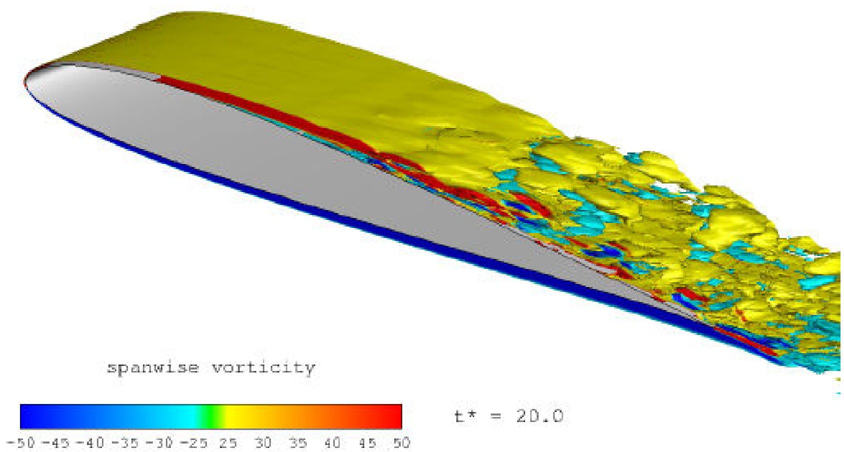

Figure 15: Transition to Turbulence Leading to Flow Separation [47]

The laminar transition to turbulent flow happens in three stages:

1. Small instabilities or disturbances generate small waves in the viscous boundary layer.
2. Instability waves grow as they move up stream.

3. Ordered laminar structures break into turbulence. This step is often ignored in calculations and the flow is assumed to be turbulent due to its short duration [50].

The source of the instabilities can be initiated from multiple sources in the MAV flow environment such as: airfoil surface roughness, turbulence of the freestream, flow unsteadiness, adverse pressure gradient, Reynolds number of the flight, vortical flow, flight kinematics, spanwise flow, and gusting [26, 50-51, 46, 30, 38]. Higher flapping frequency and amplitude creates chaotic, turbulent flow. As reviewed earlier, massive flow separation, especially at high angles of attack, produces significant flow separation and significant turbulent flow [26, 52]. Laminar flow interaction with spanwise flow can initiate the transition [26, 30, 51]. Gusting in MAV flow environments can cause transition to turbulence and full flow separation. The magnitude of gusts in MAV flow environments is high relative to MAV flight, thus allowing gusting to have significant impact on the aerodynamics. Not only can gusting affect transition on the MAV, the airflow around the many obstacles in MAV environments is often transitional and turbulent flow [38-40, 46, 51].

Nearly all transition studies agreed that accurate prediction and control of the transition from laminar to turbulent flow is critical to MAV design [1, 51, 18, 47, 53-54]. The aerodynamics are significantly different between laminar, transitional, and turbulent flow. Turbulent flow has higher shear stress than laminar flow [26, 18]. The higher shear stress can produce a momentum transport normal to the boundary layer and reattach the flow to the airfoil causing detached vortical flow to follow the airfoil surface or create a

LSB, as seen in Figure 16 below. The detached vortex following the airfoil or LSB reduces the pressure drag from unattached flow and can create a low pressure pocket to increase lift [1, 26, 30, 50, 54].

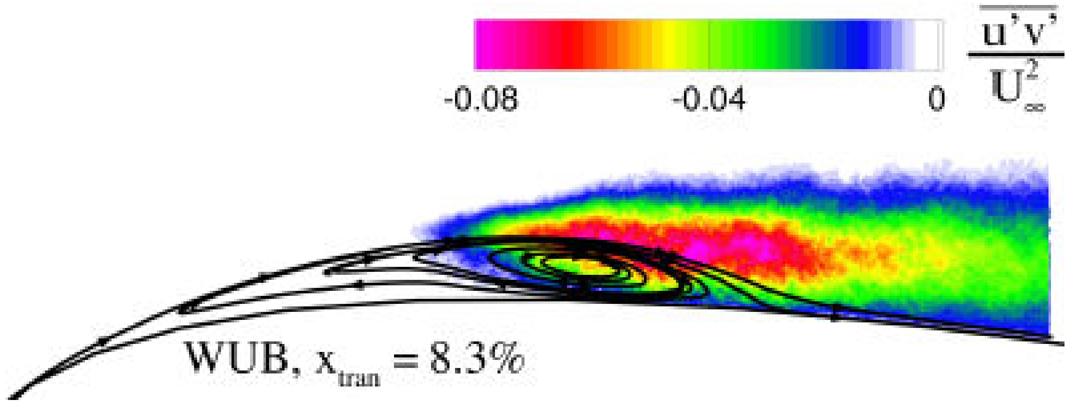

Figure 16: Turbulent Shear Causing Flow Reattachment [50]

Until recently, little has been understood about the laminar transition to turbulence on flapping airfoils, due to computational cost and difficulty of experimental methods. The simulation of laminar to turbulent transition is complex and has a high computational cost. Accurate, but cost effective simulation methods must be created. High fidelity fluid flow solvers such as LES, DNS, and RANS have had success simulating transitional flow [18, 30, 50]. Ol conducted a 3D study which compared LES and RANS solver and found that LES was more accurate predicting transition, but RANS was more accurate in deep stall situations [18, 30, 47, 50]. Yuan conducted a study of LES and DNS which was able to detect initial disturbances (Stage 1) leading to transition [30]. Different solvers are used for laminar, transitional, and turbulent flow such as the e^N

method and the k-ω model. Further development of simulation methodologies and experimental methods is needed to obtain full understanding of transition.

3.7. Laminar Separation Bubble

If flow separation reattaches to the airfoil it forms a Laminar Separation Bubble (LSB). As outlined in the Laminar Transition to Turbulence section above and Figure 12, the flow separation transitions the flow from laminar to turbulent flow. The turbulent flow has higher shear stress which produces a momentum transport normal to the boundary layer and reattaches the flow to the airfoil, which is shown in Figure 17 below [1, 26, 30, 50, 54]

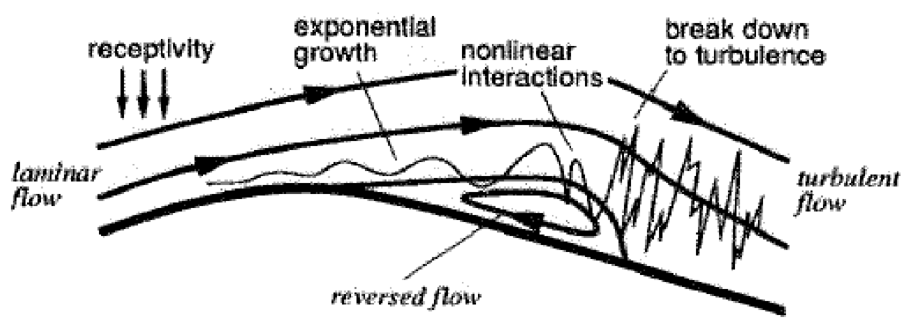

Figure 17: Laminar Separation Bubble [30]

The LSB region is characterized by a low pressure circulation pocket on the top surface of the airfoil. If the LSB is not properly controlled massive separation and stalling can ensue, producing large amounts of pressure drag. To illustrate the positive or negative effect of the LSB, Tang studied two different hovering flapping motions. In the

"Water Treading" hovering mode, the LSB reduced lift and performance, but in the "Normal" hovering mode, the LSB increased thrust and lift. The impact on overall performance is dependent on: size of LSB, airfoil surface roughness, turbulence of the freestream, flow unsteadiness, adverse pressure gradient, Reynolds number of the flight, vortical flow, flight kinematics, spanwise flow, and gusting [26, 30, 50, 55].

3.8. Leading Edge Vorticies

Leading Edge Vorticies (LEV) are created when the adverse pressure gradient and viscous shear stresses create flow separation and cause a circular vortex to break away from the leading edge of the airfoil shown in Figure 18. The LEV can follow the chord of the airfoil (desired) or completely break away from the airfoil (detrimental). If the LEV follows the surface of the airfoil, it creates a low pressure region, increasing lift. If the LEV, separates and breaks away from the airfoil the low pressure region on the top of the airfoil is not created [30, 40, 48].

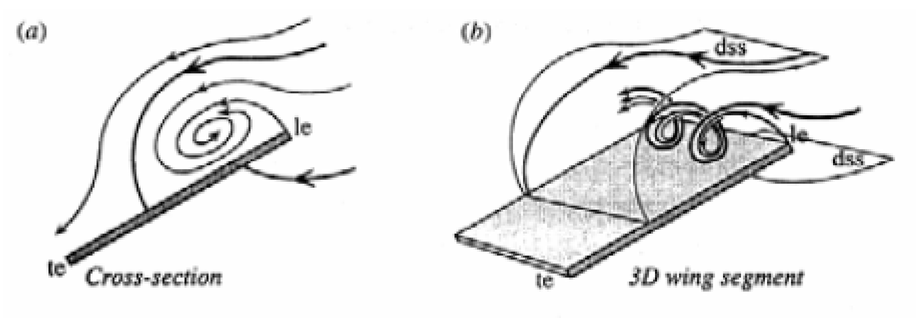

Figure 18: Leading Edge Vortex in 2D, 3D [56]

If the LEV remains attached to the airfoil it can create a condition called delayed stall. The delaying of stall increases lift and decreases drag during the flapping motion.

As described in the flow separation section, massive separation after stalling creates a significant drop in lift and significant increase in pressure drag. Delayed stall occurs when the flow over the top of the airfoil remains attached to the airfoil at airfoil positions that the airfoil would regularly stall, which are usually high angles of attack. Figure 19 below illustrates the effect of delayed stall. The green line shows the airfoil that maintained LEV attachment longer, thus achieving higher maximum lift [46, 51, 57].

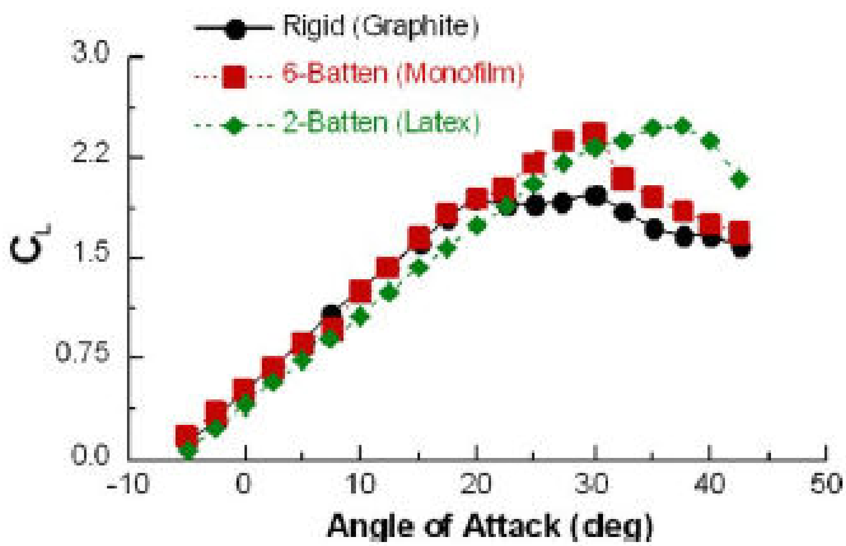

Figure 19: Delayed Stall of Airfoil [57]

LEV formation and structure is dependent on flapping kinematics, airfoil geometry, airfoil flexibility and flow conditions. There are too many kinematic variables to individually break down, but in general high angles of attack and significant leading edge motion promote LEV formation. Airfoil flexibility can help delay LEV breakdown and strengthens the LEV. The flexible airfoil directs momentum to the fluid making it more efficient [58]. In general, larger LEVs with stronger circulation create lower pressure regions and produce more lift. That is unless it causes flow separation or highly chaotic flow, which can be detrimental to performance. Proper control of the LEV aerodynamics increases lift and thrust of the airfoil and is critical to achieving optimal performance [19-20, 30, 40, 48, 52].

3.9. Trailing Edge Vorticies

Similar to LEVs, Trailing Edge Vorticies (TEV) are created when stresses cause a circular vortex to break away from the trailing edge of the airfoil. Also, when LEVs reach the trailing edge they interact with the TEVs. Even through the vorticies forms downwind from the airfoil it can interact with the LEV and Tip Vorticies (TIV) and have a significant impact on the aerodynamic performance. In instances of wake capture, the previous cycle's TEV can interact with the next flapping cycle [55].

The characteristics of the TEV can be indicative of the performance of the airfoil. Reverse Karman Vortex occurs when the TEVs of a plunging airfoil create rows of clockwise and counter-clockwise parallel vorticies, as shown in Figures 20 and 21. This vortical pattern is used as a visual indicator when the wake is producing thrust [17, 58-60].

Figure 20: Trailing Edge Vorticies [40]

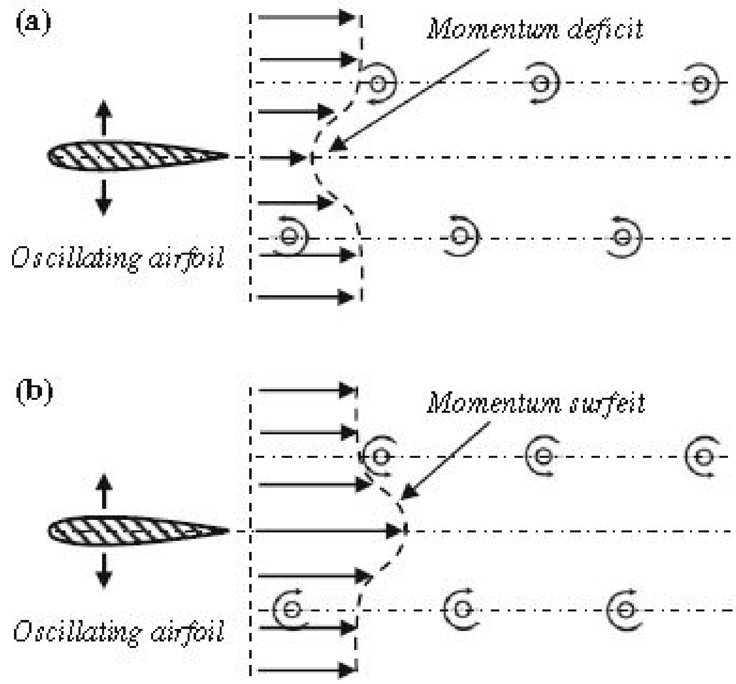

Figure 21: a) Drag Producing Wake b) Thrust Producing Wake [60]

3.10. Spanwise Flow and Tip Vorticies

Spanwise flow is flow along the airfoil cross section. Tip Vorticies (TIV) are created at the edges of the wing. The high pressure on the bottom of the airfoil flows out from under the airfoil into the freestream. Then the freestream at the edge of the airfoil is pulled onto the low pressure top side of the airfoil as shown in Figure 22 below [26].

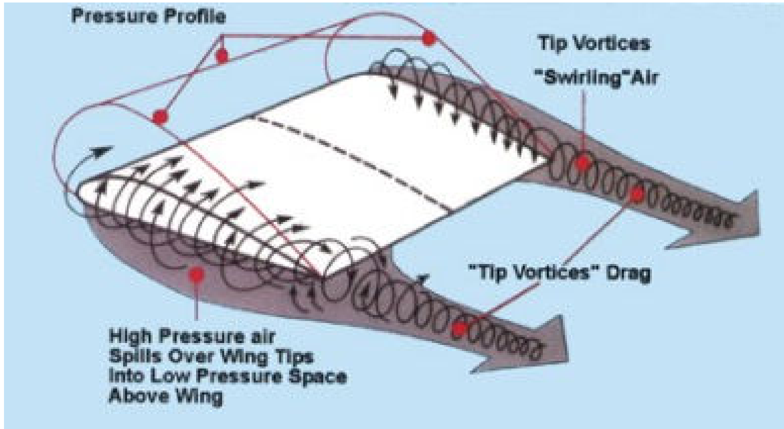

Figure 22: Tip Vortex [61]

TIVs have a significant effect on MAV wings due to the low aspect ratio of the wing. The flapping motion of the MAV increases the intensity of TIVs as well. In conventional flight, the fixed wings create TIVs that are inconsequential in comparison to the 2D aerodynamics over the length of high aspect ratio wings. The TIVs often intermingle with LEVs, TEVs, and other vortical patterns shown in Figure 23 below.

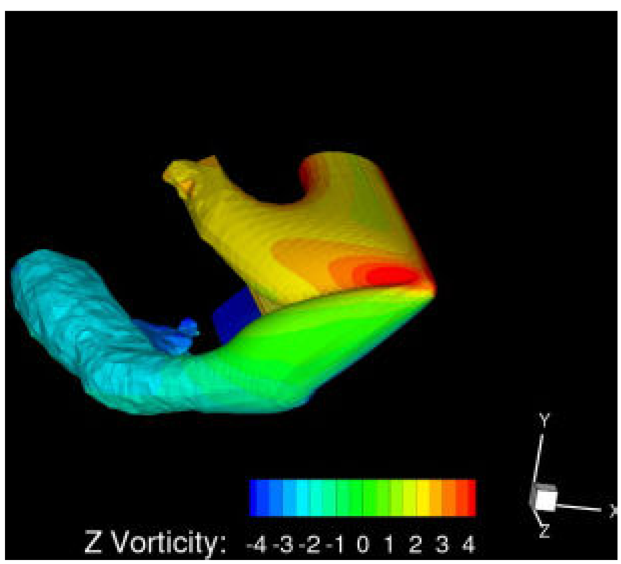

Figure 23: Spanwise Flow Resulting from Tip Vorticies [36]

There is a trade-off to the benefits of the TIV. The TIV produces a low pressure region on the top of the airfoil creating lift much like the LEV, but it also lowers the effective angle of attack lowering the lift [49, 62]. The intermingling of the vortical structures can improve the airfoil lift if controlled properly. One case of vortex interaction being detrimental in flapping motions is the production of the induced jet interaction in a study by Trizla. Induced Jet is seen in hovering motions when the TIVs create a downwash region below a specific hovering airfoil decreasing lift. This is not true for all hovering situations, but specifically for this study [36].

The TIV interacting with the LEV and TEV often stabilizes the aerodynamics and maintains stability on the airfoil preventing the vorticies from separating from the airfoil. One example of this is Doughnut Vorticies. Doughnut and Horseshoe Vorticies are formed when LEVs, TEVs, and TIVs all intermingle during flapping motions. This vortical phenomenon is a result of the LEV and TEV retaining attachment to the airfoil surface throughout the flapping down-stroke until a Horseshoe and/or Doughnut vortex is created, which often produces lift. It has been studied in the flapping motion of insects. This motion is a prime example of vortical interaction being controlled to improve the flyer's aerodynamic performance. Figure 24 below shows the doughnut and horseshoe vorticies and also illustrates the complexity of vortex interaction [31, 51].

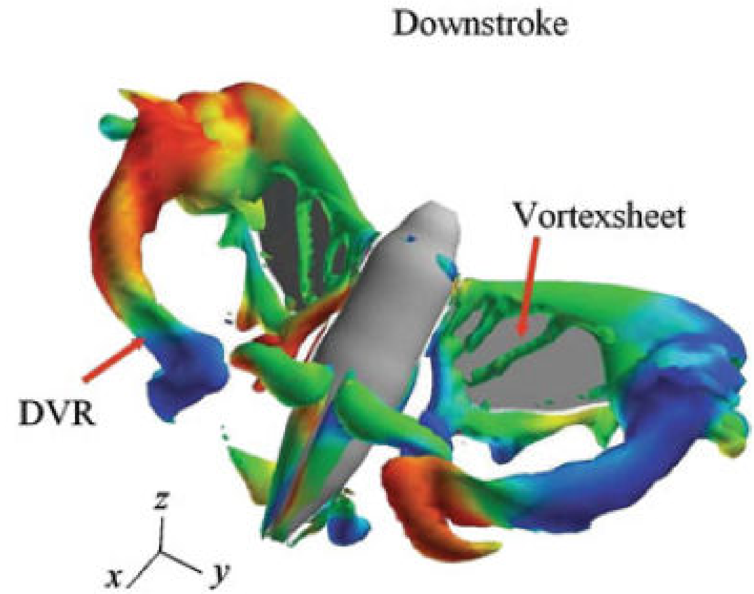

Figure 24: Doughnut Vorticies Formed from Vortex Interaction [59]

3.11. Wake Capture

Wake capture occurs when the airfoil aerodynamics come into contact with the aerodynamics of the previous cycles. This phenomenon is common in hovering and rapid flapping applications, usually when the airfoil reaches the end of flapping stroke and reverses direction as seen in Figure 25 below [46-47].

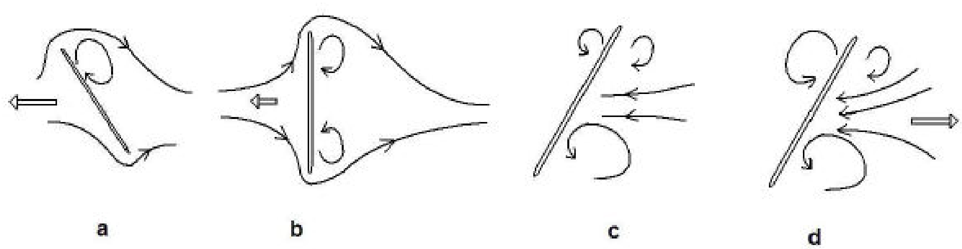

Figure 25: Wake Capture in Hover motion, a) to c) Is the Flapping Stroke Motion, d) Shows Wake Capture During Motion Reversal [46]

Wake capture is often beneficial, but can be detrimental dependent on the specific flapping kinematics. It can be beneficial when it increases the flow velocity thus increasing lift. Trizla conducted many hovering simulations with varied flapping parameters. Of the two hovering motions that experience wake capture one simulation saw increased lift from wake capture, and the other experienced a decrease in lift due to wake capture. Whether the wake capture is beneficial or detrimental, the effect on performance is usually not as significant as the lift created by delayed stall [36].

3.12. Rapid Pitch

Rapid Pitch is airfoil pitching that result from flow transition or separation. Situations like flapping stoke reversal can cause the airfoil to experience sudden, new aerodynamic forces causing a rapid pitching motion. This can enhance flow or cause instabilities if not properly controlled [47, 63].

3.13. Wake Deflection and Wake Switch

Wake Deflection is deflection of the TEV pairs from the flow direction downstream from the airfoil. Wake Switch occurs when the deflected wake switches deflection from top-side to bottom-side of the airfoil and vice versa. As the flapping frequency increases, the frequency of the wake switching increases. Even through multiple consistent flapping cycles, the wake deflects and switches at seemingly random times. The deflection and switching seems to be triggered by small disturbances in the flow, but the exact disturbance is unknown. A study by Yu, showed that an upwards deflection corresponded with positive lift. The effect on the overall aerodynamics is likely minimal, but further study is needed to determine if the effect is advantageous or detrimental [10, 17, 58, 64].

3.14. Gusting

Flapping wing MAVs are designed to fly in urban and indoor environments. In these environments gusting from multiple directions and turbulent flow is common due to the many obstacles redirecting the airflow. The low Reynolds number flight of MAVs is usually the same order of magnitude or sometimes smaller than the gusting velocity, thus the gusts create significant aerodynamic forces comparable to the flapping aerodynamics [39]. The MAVs small mass and inertia also allows the gusting to easily affect the MAV's position. The strong gusts can cause quick massive separation and stalling [19-20, 36]. Figure 26 below shows the multidirectional airflow in a room with simulated gust conditions and obstacles. In this study by Zarovay, a rotary MAV tried to land on a target in a room with gusting and multiple obstacles that caused multidirectional gusting. The MAV hit the target approximately 50% of the time. MAVs must be able to adjust and recover in these gusting situations [65].

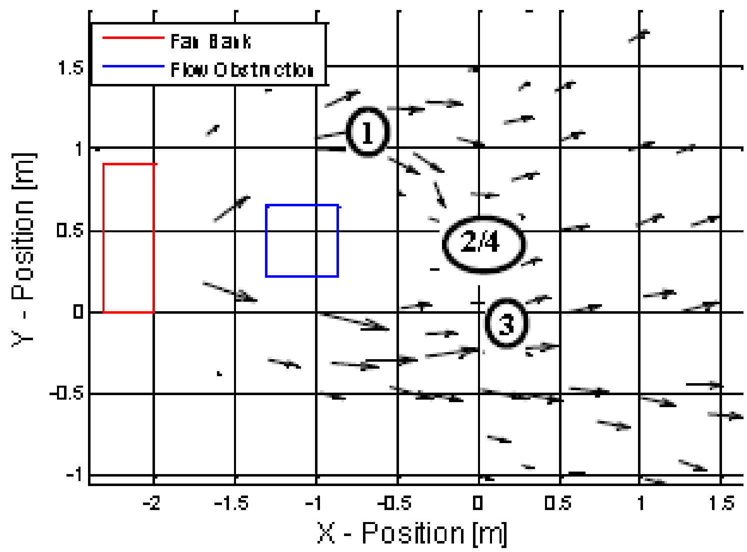

Figure 26: Gusting Airflow Around Obstacles [65]

4. GEOMETRY AND WING FLEXIBILITY CONSIDERATIONS

The geometry and flexibility of the MAV has a significant effect on its aerodynamic performance. Proper design of the geometry in junction with the stiffness of the airfoil and the flapping motions manipulates the low Reynolds number flow to achieve desired aerodynamic performance. This section will review how the geometric design can be used to increase MAV performance. Biological flyers again are used as a baseline for the design of geometry and wing structure. Many MAV wing designs utilize similar geometry as bird and insect wings. Most biological flyers have flexible wings. Birds have feathers and insects have flexible membrane spanning the skeletal structure of the wing shown in Figure 27 below [25].

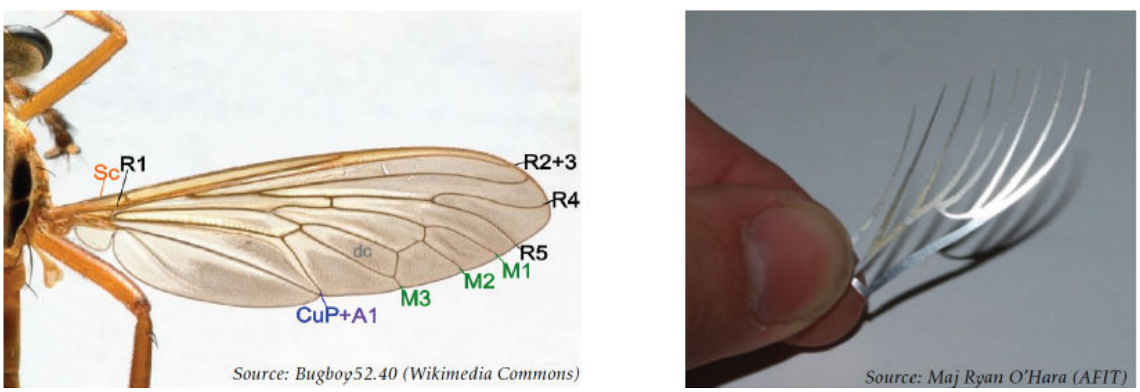

Figure 27: Insect Inspired MAV wing [25]

The 2D cross section geometry determines many of the characteristics of the aerodynamics of the wing. Thick leading edges usually increase performance, while sharp leading edges create large amounts of separation. For most MAV aerodynamics LEV creation is desired, but not massive separation and stalling. As discussed in the Low

Reynolds Number Aerodynamics section, the low aspect ratio of MAV wings in flapping flight adds complexity to the aerodynamics. If properly controlled, the spanwise flow can stabilize the LEV and TEV to delay separation and delay stalling [31, 37, 47, 51].

Adding flexibility to the MAV airfoil can significantly improve the performance of the MAV. Nearly all biological flyers have some degree of wing flexibility. The right degree of wing flexibility can result in increased lift, increased thrust, delayed stalling, and improved gust resistance. The flexibility of the airfoil helps to absorb the airflow and redirect the energy to improve performance.

4.1. Passive Pitch

Passive pitching of the airfoil is the uncontrolled pitching of the flexible airfoil as it moves through the flapping motion shown in Figure 28 below.

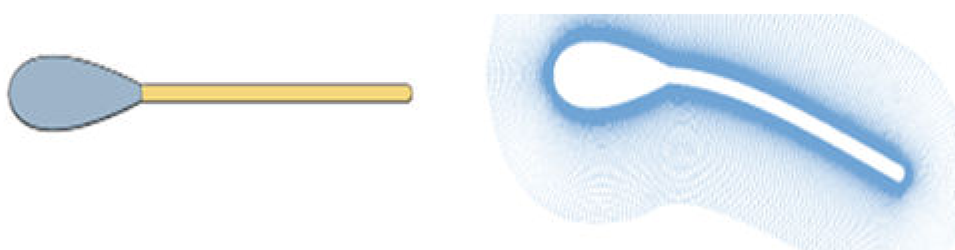

Figure 28: Passive Pitching of Flexible Airfoil [25]

With the correct amount of flexibility for the specific application, the passive pitching deformation increases the chamber of the airfoil. This can delay stall and stabilize the aerodynamics. This keeps the vorticies attached to the airfoil longer, strengthening the vorticies and imparting momentum down-stream. If the correct amount of flexibility is utilized, lift and thrust can be improved. If there is too much flexibility, the effective angle of attack of the airfoil is lowered from the deformation, which decreases lift [45, 47, 59, 66-70].

4.2. Spanwise Flow Effect

In flapping motions, the inertial load due to flapping is the highest at the tip, creating more powerful TIVs resultant again from the increased chamber. If the conditions can be correctly controlled, the flexible airfoil can create TIVs that interact with other vortical structures and stabilize them to increase thrust and lift [37, 47].

4.3. Gust Stability

Flexible airfoils passively deform to gusts and increase the stability of the airfoil. This shape adaptation allows for the flow to maintain attachment to the airfoil delaying stall. When gusting causes stalling with massive flow separation, the lift and thrust decrease significantly, and the MAV can lose its flight path if it is not able to control the aerodynamics [67-68, 71].

5. FLAPPING FLIGHT MOTION STUDIES

After the aerodynamic effects of low Reynolds number flow phenomena are understood, the aerodynamic knowledge can be applied to flapping motions design to manipulate the low Reynolds number flow phenomena and achieve desired MAV flight performance. Biological flapping motions are complex, but can be broken down into individual motions. Each individual motion has a separate effect on the flow aerodynamics and thus on the flight performance of the MAV. After understanding each motion's effect, the individual motions can be combined into complete flapping motions to achieve the desired MAV flight performance. This section reviews various flight motions and their effects on MAV flight performance and also reviews different flight modes for specific flight performance [35].

5.1. Flapping Flight Parameters

Understanding the flight parameters is important when evaluating the aerodynamics of a flapping motion. Variables like flap frequency, amplitude, flight motion, Reynolds number of flight speed, etc. For example, the optimal flapping parameters for a MAV in hover are different than a MAV in a gliding flight. The geometry of the wings, mass, and the flexibility of these wings also affects the aerodynamics of the flapping motion. Different flapping motions are also more adaptive to gusting scenarios. As an example, some of the critical parameters for a pitching motion are shown in Figure 29 below [72].

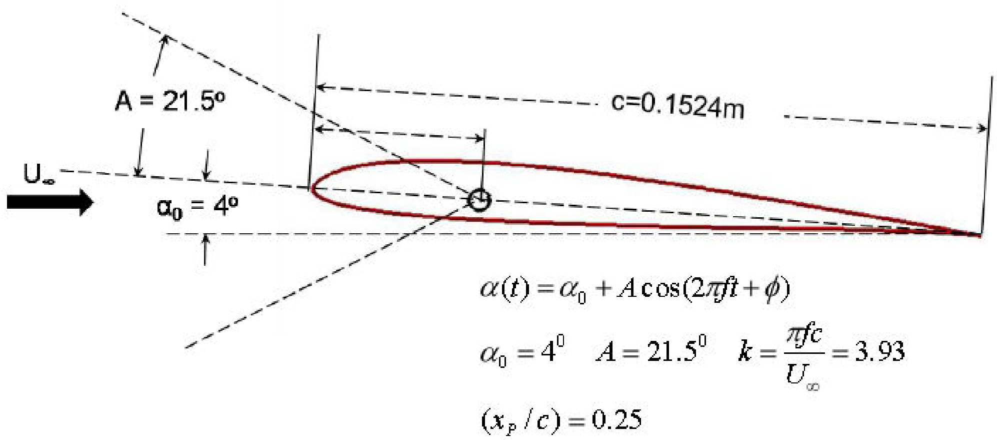

Figure 29: Key Parameters for Pitching Motion [1]

The specific flight performance objectives and limitations must be understood to determine the optimal flapping motion for each MAV. This study will review key motions that are critical in achieving performance goals.

5.2. Plunge Flight Motion

The plunging motion consists of a purely vertical up and down motion of the airfoil. This motion is common in flapping flight and is often combined with other flapping motions such as pitching. Figure 30 below shows the motion [1, 73].

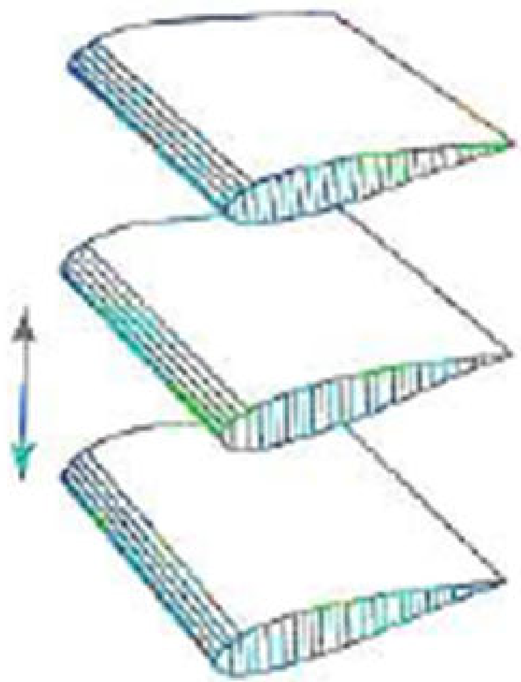

Figure 30: Plunging Motion [73]

A good way to visualize motion effects is often to compare flight to swimming. Swimming is essentially flying through water instead of air. If creating thrust in flight is compared to creating thrust while a person is swimming, the primary production of thrust is a plunging motion by the person oscillating their legs in an up and down plunging motion to push the water past their body. Like swimming, plunging motions are primary creators of thrust in MAV applications. Oscillating plunging creates a Reverse Karman Vortex pattern at nearly all flapping frequencies and amplitudes. As explained in the low Reynolds number aerodynamics section, the Reverse Karan Vortex is indicative of thrust creation [17, 45].

5.3. Pitch Flight Motion

The pitching motion consists of a rotating the airfoil's cross sectional area about an axis. This motion is common in flapping flight and is often combined with other flapping motions such as plunge. Figure 31 shows the motion. Pitching often promotes the formation of LEVs and TEVs. The bending moment of the airfoil creates a spinning vorticies at the leading and trailing edges. Proper utilization of pitching is important in creation of lift and thrust for flapping motions [1, 35, 73-74].

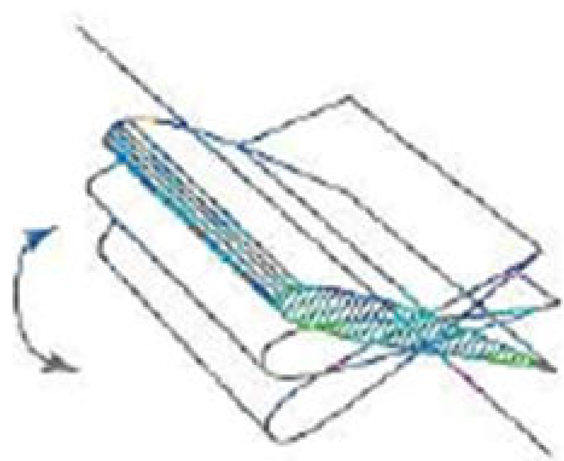

Figure 31: Pitching Motion [73]

5.3.1. Pitch Oscillations

There are many pitching motion variations within flapping cycles that can be used. The most basic motion is oscillating pitching. The up and down pitching maintains a constant pattern and frequency. This motion can produce thrust if the correct flapping frequency range is used for the specific wing [10].

5.3.2. Perching

Perching pitch motion is usually utilized by biological flyers during landing. The motion consists of the quick pitch up of the airfoil, which is held for a time. This quick pitch causes flow separation and pressure drag which slows the flyer down for landing. After this the pitched airfoil levels out. The flight motion is seen in Figure 32 below [75-76].

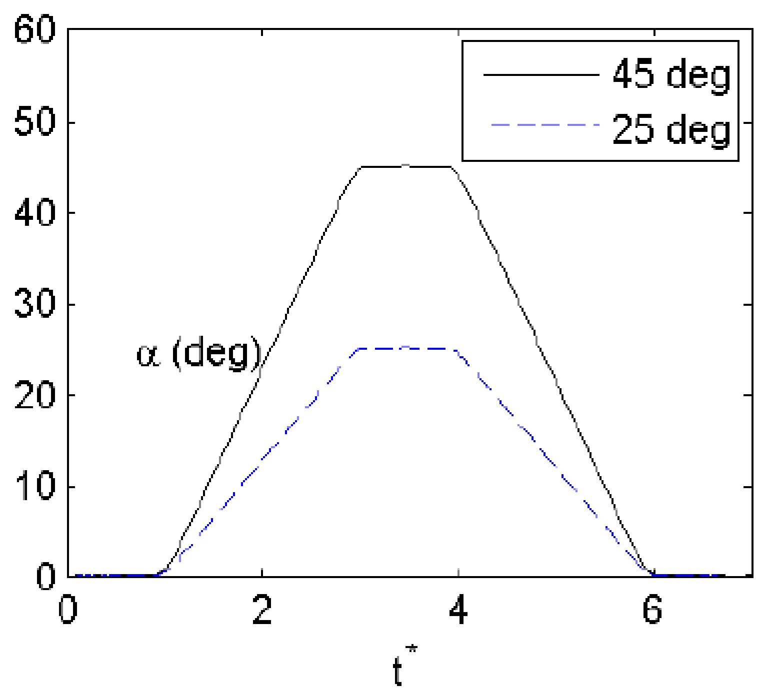

Figure 32: Perching Motion [76]

5.3.3. Passive Pitch/Twist

As previously reviewed in the Geometry and Flexibility section, Passive Pitching occurs when the wing deforms and creates a pitching motion due to the aerodynamic and inertial loads of the flapping motion. This pitching can be manipulated to improve the aerodynamic performance of the flapping motion. Passive pitching can occur along the 2D chamber as well as passive pitching of the wing tip in the spanwise direction. Passive Pitching can improve lift and thrust of the MAV if the proper wing flexibility is chosen for the wing [45, 25].

5.4. Combined Pitch, Plunge Motion

Pitch and Plunging flight motions are often combined to create better lift, thrust, and efficiency performance than either motion can achieve alone, seen in Figure 33. The pitching can be active or passive. In nature, birds and bats use active and passive pitching, while insects have no muscles in their wings and only utilize passive pitching. If the phases of the pitching and plunging oscillations are offset, it is often even more efficient. Most flight motions and all flight motions reviewed in this study involve some degree of pitching and plunging depending on the desired aerodynamic performance of the MAV [48, 73].

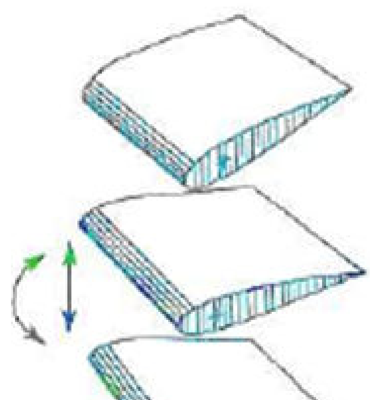

Figure 33: Pitch, Plunge Motion [73]

5.5. Hovering Motions

Hovering flight is retaining flight altitude without the flyer maintaining forward flight. Hovering flapping motions utilize combined pitching and plunging motions to produce lift. Hovering requires a high amount of power to achieve stationary flight and maintain for a long duration of time because it needs to utilize only flapping to maintain lift. In forward flight, Bernoulli's principle in airfoil shape or pitching can produce lift. Hovering flight primarily utilizes controlled, attached flow separation to create lift. If flight is again compared to a person swimming, hovering is similar to treading water. In fact, one of the primary hovering modes is called "water treading." For a person treading water, an oscillating pitching and plunging motion is used to "maintain altitude" in the water [55].

There are multiple variations of hovering that exist which can be optimized based on the MAV performance goals. The most frequently used hovering motions are shown in Figure 34 below: a) Water Treading and b) Normal Hovering [55].

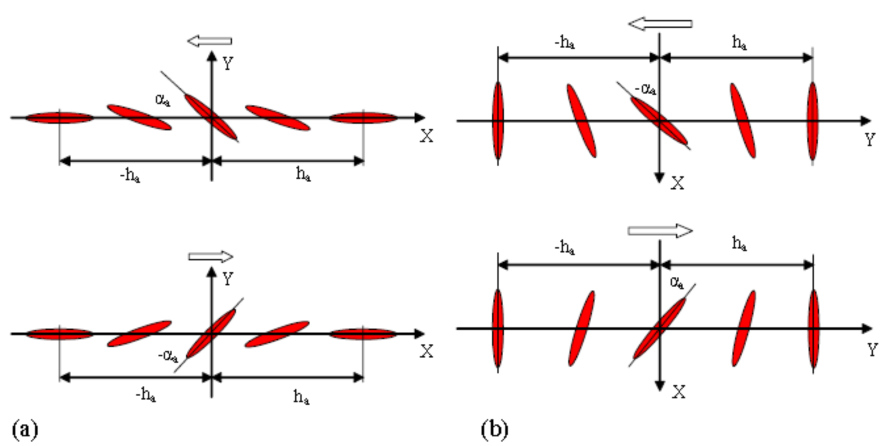

Figure 34: Hovering Modes (a) Water Tread, (b) Normal Hovering [46, 55]

The study in Figure 33 was performed by Viieru in which both hovering modes were studied. In both hovering modes, the LEV creation caused delayed stall and was the primary producer of lift. In the Water Treading hovering mode, wake capture was seen, and created an increase in lift [46, 55].

Hovering modes often require very high frequency flapping to maintain flight which creates large amounts of wake capturing. Aono studied the hovering motion of Hawkmoth moths, and saw complex interaction of LEVs, TEVs, and TIVs creating doughnut and horseshoe vorticies as seen in Figure 35 below [31, 77] .

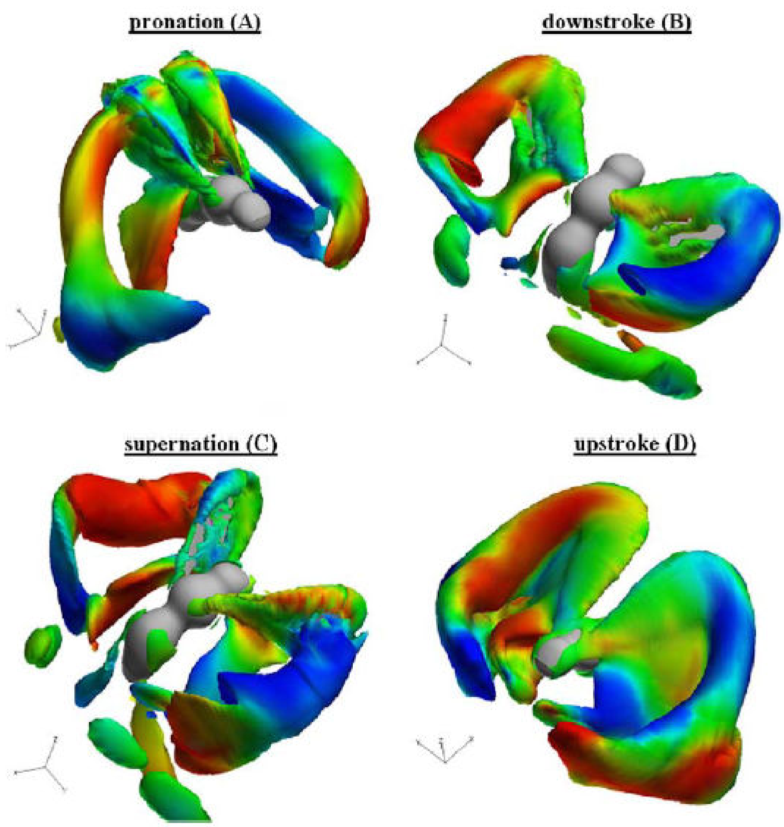

Figure 35: Aerodynamics of Hover Motion of Hawkmoth [51]

These vorticies interacted together and maintained attachment to produce sufficient lift for hovering. Proper control of the flow separation and other complex aerodynamics is critical to achieving hovering flight and maintaining it for the desired 20 minute flight time set by DARPA for NAVs. Hovering flight is one of the most difficult flapping modes to evaluate, but one of the most important because hovering creates a stationary platform for data and camera filming use of the MAV. Due to the computation cost of the high fidelity simulations or high experimental cost to accurately evaluate the complex aerodynamics of hovering flight along with DARPAs design initiatives, hovering is a difficult but critical initiative for the MAV design [31, 59, 78].

5.6. Weis Clap and Fling, Clap and Peel

Clap-and-Fling (also called Clap-and-Peel) motion is used by many insects and birds to produce lift, especially during takeoff [81]. In this pitching and plunging motion the wings pivoting about the joint quickly “clap” together. The wings then pivot, “peel,” apart which creates lift as shown in Figure 36. This motion is a slight modification to the normal hovering mode [46, 79].

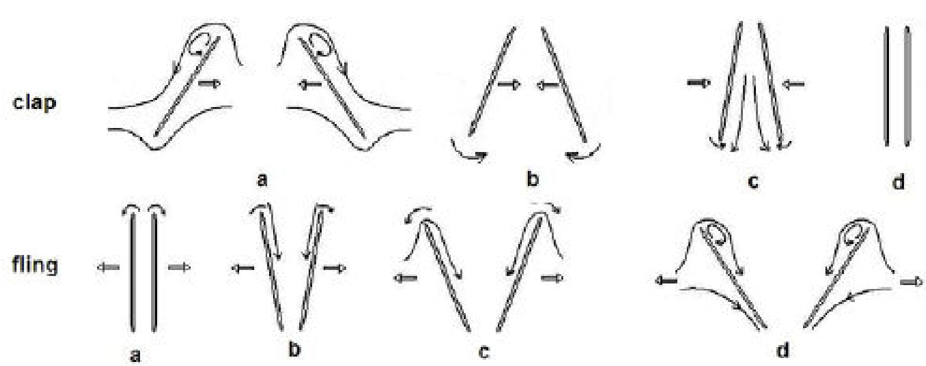

Figure 36: Clap-and-Fling Motion [79]

5.7. Figure 8 Motion

The Figure 8 flapping pattern is a slightly modified hovering pattern. The wings deviate from the purely horizontal plane and create the outline of an 8 while undergoing a pitch, plunge hovering motion as seen in Figure 37 below.

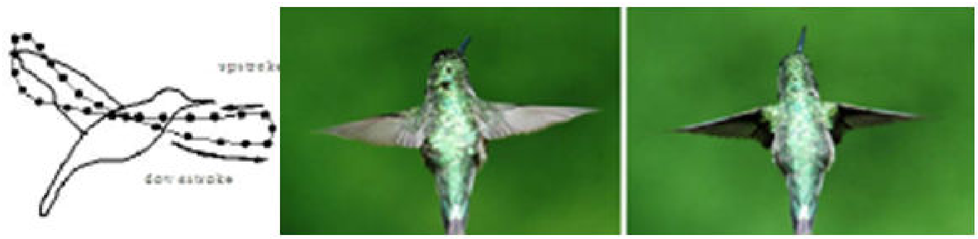

Figure 37: Figure 8 Flapping Motion in Hummingbirds [80, 51]

The Figure 8 motion is extensively used by insects and hummingbirds, which both have superior hovering, maneuverability, and stability [48]. Optimization studies have identified this motion as one of the preferred flight modes for power efficiency in hovering MAVs. Figure 38 shows a Figure 8 flapping motion for a flexible flapping wing optimized for high efficiency [25, 72].

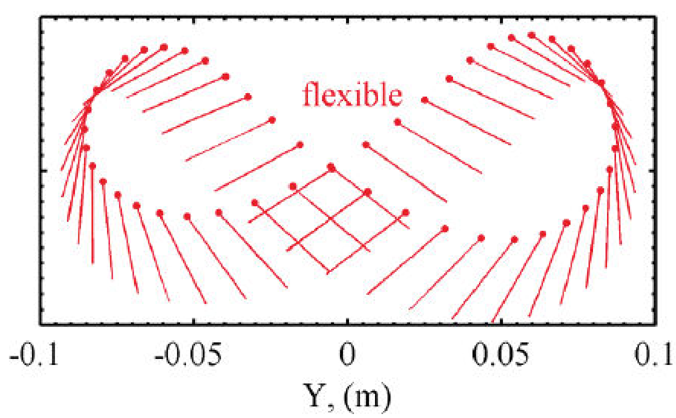

Figure 38: Figure 8 Motion [25]

5.8. Flight Modes

During flight there are multiple flight situations that require different aerodynamic performances. For example, the aerodynamic performance requirements of takeoff is different that the aerodynamic performance required for low flapping frequency soaring. The required aerodynamics of each flight mode should be evaluated to design a fully operational MAV. The performance requirements will vary based on the MAV geometry, size, airfoil structure, airfoil flexibility, and specific MAV application. For instance, a MAV design for long flight duration will be highly efficient in soaring flight with low flapping frequency, while a MAV design for maintaining hover will require higher flapping frequency and power requirements per flap cycle. The primary flight modes reviewed in this study are forward flight, lift and hover, perching, and soaring.

5.8.1. Forward Flight

Forward flight mode is simply the forward flight of the MAV. The goal is to create a substantial, but efficient amount of thrust while maintaining altitude. The motion can be as simple as a plunge or pitch and plunge motion, but can also be complex. The power requirement varies dependent on the desired flight speed. Figure 39 shows an example bird forward flight pattern [1, 25, 72-73].

Figure 39: Forward Flight Mode [81]

5.8.2. Takeoff and Hover Flight Mode

Takeoff and hovering both require a significant amount of lift during flight. For takeoff, the lift must be greater than the weight of the flyer. The motion is often more complex than the forward flight mode. Clap-and-Fling and Figure 8 motions are used by biological flyers for takeoff [82].

For the MAV to maintain hovering, the flapping motion must continuously produce the same lift as MAV weight. This flight mode requires a high amount of power, and is difficult to control for long durations of time due to flow complexity and power requirements. Only small birds and insects can maintain hover for extended lengths of time. Figure 40 below shows the bird from Figure 38 with added motion complexity due to the lower flight speed [1, 25, 72-73].

Figure 40: Low Speed Complex Flapping Motion [81]

5.8.3. Perching

Perching as reviewed earlier in this section is a common landing technique for biological flyers. The motion involves pitching the airfoil to a high angle of attack for a time inducing flow separation and pressure drag. This drag causes the flyer to slow down while still maintaining lift. The power requirement is low due to the desired decrease in lift and flight velocity [75].

5.8.4. Soaring, Gliding

The goal of Soaring and Gliding flight modes is to maintain flight with minimal power use. Soaring flight uses minimal flapping to maintain altitude and velocity. The flapping motions are usually simple pitch and plunge or U-Shaped motions which are much like forward flight motions with less frequency. Gliding flight uses gravity with the loss of altitude to maintain velocity and requires no flapping. This flight type is common in large birds during soaring. These flight modes exhibit flight characteristics much like conventional fixed wing flyers. The aerodynamics are usually characterized by low angle of attack and little flow separation, and largely laminar flow [1, 72-73].

5.9. Gust Considerations

Gusting from multiple directions is common in the small, urban environments MAVs are designed to fly in. The aerodynamic forces of gusting are often in the same level of magnitude or greater than the aerodynamics of the MAV freestream flight. These gusting forces can cause quick massive separation and stalling of the airfoil. The flapping kinematics must have the ability to recover from the gusts and retain stable flight in gusting conditions. Modification to flapping motions can minimize gusting effects. Figure 41 below illustrates the flapping frequency of biological flyers in comparison to their flight speed [19-20, 36].

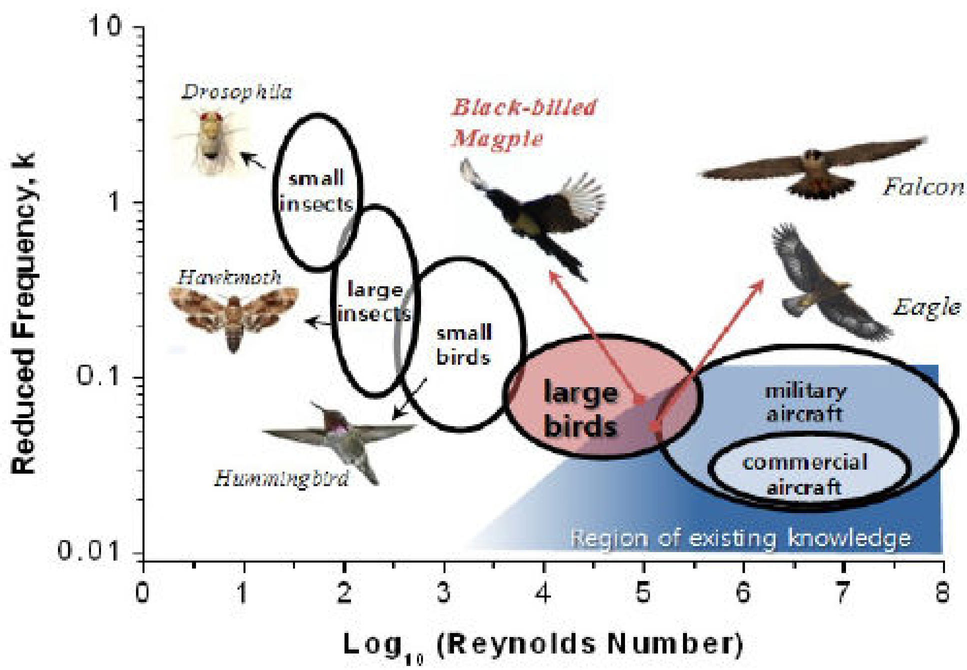

Figure 41: Biological Flyers' Flapping Frequency vs Flight speed [77]

Very low Reynolds Number or hovering flyers have common characters. They all have low mass (like MAVs) and high flapping frequency. High frequency flapping can improve performance in gusting. After wind gusts sweep the vorticies off the airfoil, the following flapping cycle or series of flapping cycles are able to quickly recreate aerodynamics needed to maintain flight [36].

Another technique to adjust for gusting is to utilize flexible airfoils. Flexible airfoils are able to adapt to the flow and redirect it to minimize the gust effect. The wing deformation can delay stalling of the airfoil as discussed in the Geometry and Wing Flexibility section. Airfoil geometry can also be adjusted to better accommodate gusting, but this is specific to each MAV design [67-68, 71].

6. MAV OPTIMIZATION STUDIES

The process of determining the optimal flapping flight conditions has an overwhelming amount of design variables that need to be determined for each MAV application. Optimization techniques are developed to help determine the design direction by saving testing time, computational cost, and minimizing the time of researching all variables individually. Often it is more cost effective for the design process to design an optimization methodology to evaluate variables than creating an established design before optimization. Optimization techniques can be utilized in experimental or computational studies to save design cost, but with the advancements in recent years in computational power, design time can be greatly reduced by utilizing simulations. Expensive experiments are then only used to justify simulation results [25, 35].

Nearly all design variables can use optimization techniques of some kind. First the primary performance objectives are chosen such as: max lift, max thrust, propulsive efficiency, etc. Then the design variables are identified such as: wing geometry, flight conditions, flapping kinematics, wing flexibility, etc. Surrogate Modeling optimization determines the sensitivity of each variable and reduces the amount of simulations by reducing the variables and variable ranges. Optimization techniques can conduct wide range simulations with low fidelity computation methods, which have less computational cost. Then optimization model simulates high fidelity, expensive, computations after the optimal range is determined for sufficient accuracy. Pareto Fronts can be used in junction with Surrogate Modeling to evaluate variables with conflicting objectives. An example of the use of a Pareto Front would be in a situation that a high angle of attack pitching of the airfoil might increase lift, but also increase drag. The Pareto Front would evaluate the trade-offs of each variable and choose variable values to optimize the motion for the chosen performance objectives. Shown in Figure 42 below are optimized wing structures from an optimization study by Snyder [25, 35, 48, 72, 83].

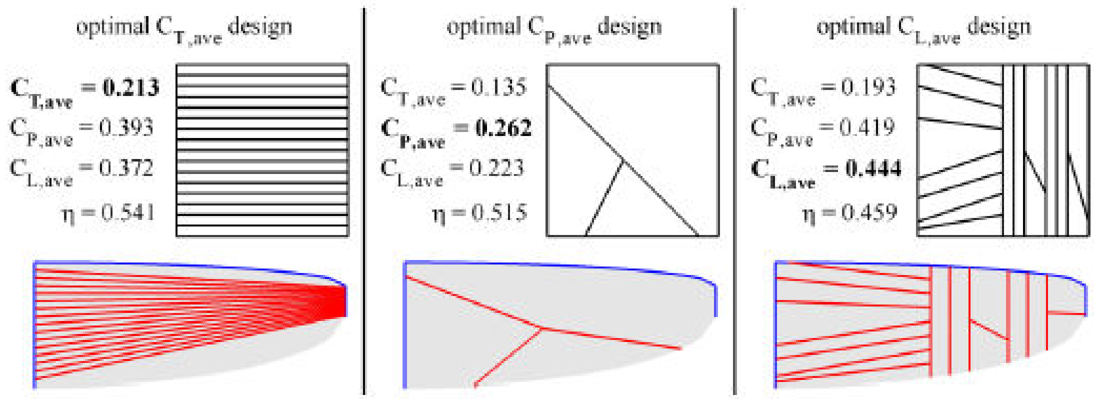

Figure 42: Optimized Wing Geometries [25]

In an example study by Dong, optimal flight kinematics were chosen for three separate flight modes: maximum lift, maximum propulsive efficiency, and minimal flight noise (quiet, smooth flight). For maximum lift, the optimal flapping motion used a hovering motion with a high angle of attack. For maximum efficiency, the optimal flapping motion used a Figure 8 motion, with decreased flapping amplitude. For minimal flight noise, the optimal flapping motion used a U-shaped motion with high flapping amplitude. These optimization techniques choose unique flight conditions for each flight mode based on the design performance goals [72].

7. SPECIFIC MAV DESIGNS DETAILS

In the past several years, several unique flapping wing MAV designs have been created. This section reviews two of the more promising MAV designs and highlights areas of potential growth to further advance MAV capabilities.

7.1. Robot Insect

The Robot Insect was developed by Wood. The Robot Insect is a flapping wing MAV with flexible wings similar in skeletal-membrane structure to Diptera insect wings, seen in Figure 43 below. The flapping motion is modeled after Diptera insects as well. The design has the potential to meet the stringent DARPA NAV design goals. The Robot Insect is only 60 mg and about the size of a coin. It is able to maintain hovering flight and follow a GPS programmed path. However, the MAV is not capable of flight without an external power cord tethered to the power source [84-85].

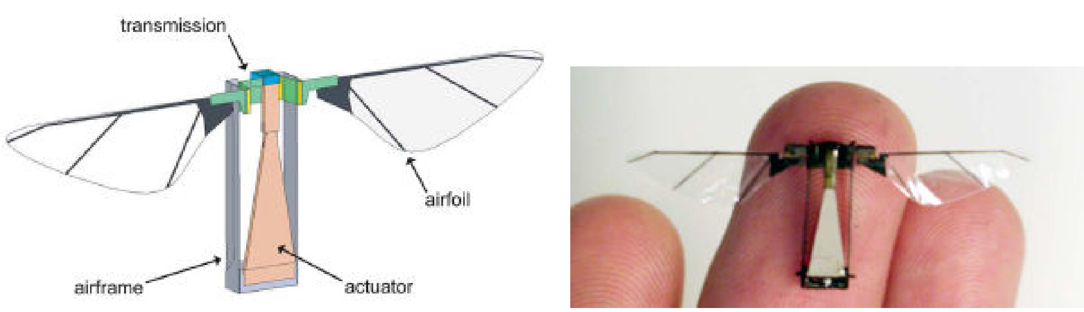

Figure 43: Robot Insect [84]

7.2. Aerovironment Hummingbird

The Aerovironment Hummingbird is one of the most promising fully operational MAVs, shown in Figure 44. It mimics the shape and flapping kinematics of a hummingbird. The Hummingbird weighs 19g with a length of 16cm, which meets the DARPA MAV design initiatives. The Hummingbird is capable of controlled flight and hover, while also carrying a camera. It is able to maintain controlled flight outdoors and indoors. [25, 86].

Figure 44: Aerovironment Nanohummingbird [6]

8. CLOSING REMARKS AND RECOMMENDATIONS FOR FUTURE STUDY

The overall goal of MAVs is to emulate the high maneuverability, high efficiency flight of biological flyers in low Reynolds number, confined space flight environments. The goal of this study was to perform a literature review of the state of the art of the aerodynamics of flapping wing flight in MAV applications. In the last 25 years, the understanding of flapping wing aerodynamics has increased exponentially. The development of better experimental and simulation methodology has allowed for highly accurate measurement and thus characterizing of complex low Reynolds number aerodynamics. The understanding of the effect of the aerodynamics has been used to develop MAV geometry design, wing flexibility design, and flapping motions to manipulate the low Reynolds aerodynamics to achieve desired flight performance for the specific flight mode. Optimization techniques have been used to optimize the numerous design variables to achieve optimal flight performance. Several MAV designs have now been developed that are fully functional and meet MAV design goals.

Despite the vast amount of data that has been acquired to understand flight aerodynamics, many aspects of MAV design still need development. Better understanding of the interaction between flapping kinematics and the flapping aerodynamics is needed. This will result in more efficient flight performance and development of better control systems. Better control systems will improve MAV flight control and ability to better adjust for gusting. As computational power increases and computational cost continues to decrease, the ability to perform more detailed and accurate computations will increase understanding of flapping wing aerodynamics. The increasing computational power also allows for more detailed and higher fidelity optimization methods that can account for more variables. Along with experimental and computational advancements in the last 20 years, there has been rapid advancement in materials science, battery life, control system capabilities, etc. The NAV and MAV design initiatives can be developed to further reflect the capabilities of the state of the art. Of the MAV and NAV design constraints, flight endurance of greater than 20 minutes is one of the most difficult design goals to achieve. Further battery life advancements along with more efficient flapping models should make this design goal feasible [2, 38, 47, 82-83].

In general there is still a wide gap between the flapping flight performance of man-made flyers and biological flyers in low Reynolds number flow environments. Understanding the current state of the art of flapping wing aerodynamics and proper application of this knowledge to specific MAV design will result in MAV designs that are even more comparable to biological flyer flight performance in MAV applications.

REFERENCES

[1] Alam, M. (2008). Numerical Investigation of Low Reynolds Number Pitching Airfoil Flowfiields for Micro Air Vehicle Applications (Master's Thesis). North Dakota State University, Fargo ND.

[2] Liu, Z., & Moschetta, J.-M. (2009). Rotary vs Flapping-Wing Nano Air Vehicles Comparing Hovering Power.

[3] Atkinson, B. (n.d.). *Military's Hummingbird Micro-UAVs*. Retrieved May 2014, from http://cydro.hubpages.com/hub/Backpack-UAVs-Militarys-RC-planes-have-proven-their-worth

[4] Ifju, P. G., Jenkins, D. A., Ettinger, S., Lian, Y., Shyy, W., & Waszak, M. R. (2002). Flexible-Wing-Based Micro Air Vehicle. *American Institute of Aeronautics and Astronautics*.

[5] *Prox Dynmaics*. (n.d.). Retrieved from http://www.proxdynamics.com/.

[6] Sanjay. (2011, September). *Aerosapien*. Retrieved from http://aerosapien.blogspot.com/2011/09/nano-humming-bird-doc-except-for.html

[7] Han, J.-H., Lee, J.-S., & Kim, D.-K. (2009). Bio-Inspired Flapping UAV Design: A University Perspective. *Proceedings of SPIE, 7295*.

[8] Petricca, L., Ohlckers, P., & Grinde, C. (2011). Micro- and Nano-Air Vehicles: State of the Art. *International Journal of Aerospace Engineering*, 1-17.

[9] Love, R. D. (2009). Time-Frequency Analysis of Aeroelastic Deformations of Flapping Wings. *American Institute of Aeronautics and Astronautics* .

[10] Yu, M. L., Hu, H., & Wang, Z. J. (2012). Experimental and Numerical Investigations on th Asymmetric Wake Vortex Structures and an Oscillating Airfoil. *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*.

[11] Hu, H., Kuman, A., Abate, G., & Albertani, R. (2009). An Experimental Investigation on the Aerodynamic Performance of flexible membrane wings in flapping flight. *Aerospace Science and Technology*, 575-586.

[12] Rue, J., Change, K., Ifju, P., Haftka, R., Schmitz, T., McIntrie, J., Chaudhuri, A. (2012). Fabrication and Analysis of Small Flapping Wings.

[13] *Fly* . (2014). Retrieved from Leonardo da Vinci, The Complete Works: http://www.leonardoda-vinci.org/fly.html

[14] Knoller, R. (1909). Die Gestze des Luftwiderstandes. *Flug-und Motortechnik, 3*, 1-9.

[15] Betz, A. (1912). Ein Bitrag zur Erklaerung des Segelfluges. *Zeitschrift fuer angewandte Flugtechnik und Motorluftschiffahrt, 3*, 269-272.

[16] von Karmen, T., & Burgers, J. (1943). General Aerodynamic Theory - Perfect Fluid. *Aerodynamic Theory, 2*, 308.

[17] Jones, K. D., Dohring, C. M., & Platzer, M. F. (1998). Experimental and Computational Investigation of the Knoller-Betz Effect. *AIAA Journal*, 1240-1246.

[18] Ol, M. V. (2010). Some Observations on Periodic and Transient Motions on MAV-Relevant Unsteady Aerodynamics.

[19] Granlund, K., Ol, M., & Bernal, L. (2011). Experiments on Pitching Plates: Force and Flowfield Measurements at Low Reynolds Numbers. *48th AIAA Aerospace Sciences Meeting Including the New Horzons Forum on Aerospace Exposition.* Orlando, FL.

[20] Granlund, K., Ol, M., & Bernal , L. (2011). Flowfield Evolution vs Lift Coefficient History for Rapidly-Pitching Low Aspect Ratio Plates. *6th AIAA Theoretical Fluid Mechanics Conference.* Honolulu, HI.

[21] Ol, M., & Gharib, M. (2001). The Passage Towards Stall of Nonslender Delta Wings at Low Reynolds. *31st AIAA Fluid Dynamics Conference and Exhibit*.

[22] Freymuth, P. (1990). Thrust Generation by an Airfoil in Hover Modes. *Experiments in Fluids, 9*, 17-24.

[23] Aono , H., Chimakurthi, S. K., Wu, P., Sallstrom, E., Stanford, B. K., Cesnik, C. E., . . . Shyy, W. (2010). A Computational and Experimental Study of Flexible Flapping Wing Aerodynamics. *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*.

[24] DeLuca, A., Reeder, M., Freeman, J., & Ol, M. (2005). Flexible- and Rigid-Wing Micro Air Vehicle: Lift and Drag Comparison. *Journa of Aircraft, 43*(2), 572-575.

[25] Snyder, R. D., Beran, P., & Kolonay, R. (2012). *Physics-Based Design of Micro Air Vehicles.* Wright-Patterson Air Force Base, OH: Air Force Research Lab.

[26] Anderson, J. D. (2007). *Fundamentals of Aerodynamics, 4th Edition.* New York, NY: McGraw-HIll.

[27] Jones, K., Dohring, C., & Platzer, M. (1996). Wake Structures Behind Plunging Airfoils: A Comparison of Numerical and Experimental Results. *34th Annual Aerospace Sciences Meeting and Exhibit.* Reno, NV: AIAA.

[28] *Navier-Stokes Equations*. (12, June 2014). Retrieved from Wikipedia: http://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations

[29] Kumar, K., & Sajjan, S. (2011). Unsteady Flow Past a Combined Pitching and Plunging Aerofoil using an Implicit RANS Solver. *2011 International Conference on Mechanical and Aerospace Engineering*, (pp. 74-78).

[30] Yuan, W., Khalid, M., Windte, J., Scholz, U., & Radespiel, R. (2007). Computational and Experimental Investigations of Low-Reynolds-Number Flow Past Airfoils. *The Aeronautical Journal*, 17-29.

[31] Aono, H., Shyy, W., & Liu, H. (2009). Near Wake Vortex Dynamics of a Hovering Hawkmoth. *Aeta Mech Sin, 25*, 23-36.

[32] Su, W., & Cesnik, C. (2009). Coupled Nonlinear Aeroelastic and Flight Dynamic Simulation of a Flapping Wing Micro Air Vehicle. *Department of Aerospace Engineering, The University of Michigan*.

[33] Trizla, P., Kang, C., Aono, H., Visbal, M., & Shyy, W. (2011). Low-Reynolds-number Aerodynamics of Flapping Rigid Flat Plate. *AIAA Journal, 49*(4), 806-823.

[34] Kang, C.-k., & Shyy, W. (2012). Effects of Flexibility on Aerodynamics of a Hovering Airfoil at Reynolds Number of 100 to 1000. *50th AIAA Aerospace*

Sciences Meeting Including th New Horizons Forum and Aerospace Exposition. Nashville Tennessee.

[35] Trizla, P. C., Kang, C.-K., Visbal, M. R., & Shyy, W. (2008). Unsteady Fluid Physics and Surrogate Modeling of Low Reynolds Number, Flapping Airfoils. *38th Fluid Dynamics Conference and Exhibit.* Seattle, Washington.

[36] Trizla, P., Kang, C.-K., Aono, H., Visbal, M., & Shyy, W. (2010). Fluid Physics of Surrogate Modeling of a Low Reynolds Number Flapping Rigid Flat Plate. *28th AIAA Applied Aerodynamics Conference*.

[37] Taira, K., & Colonius, T. (2009). Three-dimensional Flows Around Low-aspect-ratio Flat-plate wings at Low Reynolds Numbers. *Journal of Fluid Mechanics*, 187-207.

[38] Abdulrahim, M., Watkins, S., Segal, R., & Marino , M. (2010). Dynamic Sensativity to Atmospheric Turbulence of Unmanned Air Vehicles with Varying Configuration . *Journal of Aircraft*, 1873-1883.

[39] Jenkins, D., Ifju, P., Abdulrahim, M., & Olipra, S. (2001). Assessment of the Conrollability of Micro Air Vehicles. *Bristol International RPV/UAV Conference.* Bristol, UK.

[40] Lian, Y., & Shyy, W. (2007). Aerodynamics of Low Reynolds Number Plunging Airfoil under Gusty Environment. *45th AIAA Aerospace Sciences Meeting and Exhibit*.

[41] *Vortex*. (2014, May 12). Retrieved from Wikipedia: http://en.wikipedia.org/wiki/Vortex

[42] Anderson, J. D. (1985). *Fundamentals of Aerodynamics.* New York, NY: McGraw-Hill.

[43] *Boundary Layer Theory*. (2010, July). Retrieved from Thermal-Fluids Central: https://www.thermalfluidscentral.org/encyclopedia/index.php/Boundary_layer_theory#equation_.286.29

[44] *Inclination Effects of Lift*. (2014, June 12). Retrieved from NASA : http://www.grc.nasa.gov/WWW/Wright/airplane/incline.html

[45] Heathcote, S., Martin, D., & Gursul, I. (2004). Flexible Flapping Airfoil Propulsion at Zero Freestream Velocity. *AIAA, 42*(11), 2196-2204.

[46] Viieru, D., Tang, J., Lian, Y., Liu, H., & Shyy, W. (2006). Flapping and Flexible Aerodynamics of of Low Reynolds Number Flight Vehicles. *44th AIAA Aerospace and Sciences Meeting and Exhibit.* Reno, NV.

[47] Shyy, W., Aono, H., Chimakurthi, S. K., Trizla, P., Kang, C. K., Cesnik, C. E., & Liu, H. (2010). Recent Progress in Flapping Wing Aerodynamics and Aeroelasticity. *Progress in Aerospace Science* , 284-327.

[48] Platzer, M., & Jones, K. (2006). Flapping Wing Aerodynamics - Progress and Challenges. *44th AIAA Aerospace Sciences Meeting and Exhibit.* Reno, NV.

[49] Shyy, W., Ifju, P., & Viieru, D. (2005). Membrane-Wing Based Micro Air Vehicles. *ASME Applied Mechanics Reviews*, 283-301.

[50] Radespiel, R., Windte, J., & Scholz, U. (2006). Numerical and Experimental Flow Analysis of Moving Airfoils with Laminar Separation Bubbles. *44th AIAA Aerospace Sciences Meeting and Exhibit*.

[51] Shyy, W., Lian, Y., Tang, J., Liu, H., Trizla, P., Stanford, B., . . . Ifju, P. (2008). Computational Aerodynamics of Low Reynolds Number Plunging, Pitching, and Flexible Wings for MAV Applications. *Achta Machanica Sinica*.

[52] Zaman, R. I., Lai, J. C., Young, J., & Ashraf, M. A. (2012). Flow Periodicity Analysis of Low Reynolds Number Flapping Airfoils. *18th Australasian Fluid Mechanics Conference.* Launceston, Austrailia.

[53] Biber, K., Ol, M. V., & Tilmann, C. P. (2004). Some Examples of Airfoil Design For Future Unmanned Air Vehicle Concepts. *42nd AIAA Aerospace Sciences Meeting and Exhibit*.

[54] Uranga, A., Persson, P.-O., Drela, M., & Peraire, J. (2010). Implicit Large Eddy Simulation of Transitional Flows Over Airfoils and Wings. *19th AIAA Computatonal Fluid Dynamics*.

[55] Tang, J., Viieru, D., & Shyy, W. (2007). Effects of Reynolds Number and Flapping Kinematics on Hovering Aerodynamics. *45th AIAA Aerospace Sciences and Meeting Exhibit*.

[56] Berg van den, C., & Ellington, C. P. (1997). The Three Dimensional Leading-Edge Vortex of a 'Hovering' Model Hawkmoth. *Philosophical Transactions of Royal Society of London, 352*, 329-340.

[57] Lian, Y., Shyy, W., Viieru, D., & Zhang, B. (2003). Membrane Wing Aerodynamics for Micro Air Vehicles. *Progress in Aerospace Sciences, 39*, 425-465.

[58] Heathcote, S., & Gursul, I. (2007). Jet Switching Phenomenon for a Periodically Plunging Airfoil. *Physics of Fluids*.

[59] Liu, H., Nakata, T., Gao, N., Mada, M., Aono, H., & Shyy, W. (2010). Micro Air Vehicle-motivated Computational Bio-mechanics in Bio-flights: Aerodynamics, Flight Dynamics, and Maneuvering Stability.

[60] Hu, H., Clemons, L., & Igarashi, H. (2011). An Experimental Study of the Unsteady Vortex Structures in the Wake of a Root-fixed Flapping Wing. *Experimental Fluids, 51*, 347-359.

[61] *Wing Vorticies*. (2014). Retrieved from Pilot Friend: http://www.pilotfriend.com/training/flight_training/aero/wng_vort.htm

[62] Lian, Y., & Shyy, W. (2003). Shape Optimization of a Membrane Wing for Micro Air Vehicle Applications. *AIAA*.

[63] Dickinson, M., Lehmann, F., & Sane, P. (1999). Wing Rotation and the Aerodynamic Basis of Insect Flight. *Science*, 1954-1960.

[64] Lai, J., & Platzer, M. (1999). Jet Characteristics of a Plunging Airfoil. *AIAA Journal, 37*(12), 1529-1537.

[65] Zarovy, S., Costello, M., Mehta, A., Flynn, A., Gremillion, G., Miller, D., . . . Humbert, J. S. (2010). Experimental Study of Gust Effects on Micro Air Vehicles. *American Institute of Aeronautics and Astronautics*.

[66] Niu, Y.-Y., Liu, S.-H., Chang, C.-C., & Tseng, T. (2012). A Preliminary Study of Three-Dimensional Aerodynamics of Flapping Wings. *Journal of Applied Science and Engineering*, 257-263.

[67] Waszak, R. M., Jenkins, N. L., & Ifju, P. (2001). Stability and Control Properties of an Aeroelastic Fixed Wing Micro Aerial Vehicle. *American Institute of Aeronautics and Astronautics*.

[68] Lian, Y., & Shyy, W. (2005). Numerical Simulations of Membrane Wing Aerodynamics for Micro Air Vehicle Applications. *Journal of Aircraft*, 865-873.

[69] Tobing , S., Young, J., & Lai, J. C. (2010). Effects of Aeroelasticity of Flapping Wing Propulsion. *17th Austrailian Fluid Mechanics Conference*.

[70] Pederzani, J., & Haj-Hairiri, H. (2006). Numerical Analysis of Heaving Flexible Airfoils in a Viscous Flow. *AIAA Journal 44*, 2773-2779.

[71] Stanford, B., Ifju, P., Albertani, R., & Shyy, W. (2008). Fixed Membrane Wings for Micro Air Vehicles: Experimental Characterization, Numerical Modeling, and Tailoring.

[72] Dong, H., Lian, Z., & Harff, M. (2009). Optimal Settings of Performance Parameters in Hovering Flight. *International Journal of Micro Air Vehicles* , 173-191.

[73] Shyy, W., Lian, Y., Tang, J., & Viieru, D. (2008). Aerodynamics of Low Reynolds Number Flyers. *Cambridge Aerospace Series, Cambridge University Press*.

[74] Sun, M., & Tang, J. (2002). Unsteady Aerodynamic Force Generation by Model Fruit Fly Wing in Flapping Motion. *Journal of Experimental Biology, 205*, 55-70.

[75] Baik, Y. S., Aono, H., Rausch, J. M., Bernal, L. P., Shyy, W., & Ol, M. V. (2010). Experimental Study of Rapidly Pitched Flat Plate at Low Reynolds Number. *40th Fluid Dynamics Conference and Exhibit*.

[76] Ramesh, K., Gopalarathnam, A., Edwards, J. R., Ol, M. V., & Granlund, K. (2011). Theoretical, Computational, and Experimental Studies of a Flat Plate Undergoing High-Amplitude Pitching Motion. *American Institude of Aeronautics and Astronautics*.

[77] Leishman, J. G. (2006). *Principles of Helicopter Aerodynamics, 2nd Edition* . Cambridge Aerospace Series.

[78] Pines , D., & DARPA/DSO. (n.d.). *Nano Air Vehicle Program BAA06-06*.

[79] Weis-Fogh, T. (1973). Quick Estimate of Flight Fitness in Hovering Animals, Including Novel Mechanisms for Lift Production. *Journal of Experimental Biology, 59*, 169-230.

[80] Azuma, A. (1992). *The Biokinetics of Flying and Swimming.* Tokyo: Springer-Verla.

[81] Tobalske, B. W., & Dial, K. P. (1996). Flight Kinematics of Black-Billed Magpies and Pigeons Over a Wide Range of Speeds. *Journal of Experimental Biology, 199*, 263-280.

[82] Richter, C., & Lipson, H. (2011). Untethered Hovering Flapping Flight of 3D Printed Mechanical Insect. *Artifical Life*, 73-86.

[83] Kang, C.-k., Aono, H., & Cesnik, C. (2011). A Scaling Parameter for the Thrust Generation of Flapping Flexible Wings. *49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition.* Orlando, FL.

[84] Wood, R. J. (2008). The First Takeoff of a Biologically Inspired At-Scale Robot Insect. *IEEE Transactions on Robotics*, 341-347.

[85] Feltman, R. (2013, May). Robotic Housefly Buzzes to Life. *Popular Mechanics*.

[86] AeroVironment, Inc. (2011). Aerovironment Develops World's First Fully Operational Life-Sized Hummingbird-Like Unmanned Aircraft for DARPA. *Press Release*.