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MEMS Based Micro Aerial Vehicles

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Abstract. Designing a flapping wing insect robot requires understanding of insect flight mechanisms, wing kinematics and aerodynamic forces. These subsystems are interconnected and their dependence on one another affects the overall performance. Additionally it requires an artificial muscle like actuator and transmission to power the wings. Several kinds of actuators and mechanisms are candidates for this application with their own strengths and weaknesses. This article provides an overview of the insect scaled flight mechanism along with discussion of various methods to achieve the Micro Aerial Vehicle (MAV) flight. Ongoing projects in Chalmers is aimed at developing a low cost and low manufacturing time MAV. The MAV design considerations and design specifications are mentioned. The wings are manufactured using 3D printed carbon fiber and are under experimental study.

1. Introduction

During the past decade the research on insect flight has substantially altered our understanding of aerodynamics, neuroscience and the flight mechanism of insects. This understanding promoted the research on Micro Aerial Vehicle(MAV) in the field of Micro Electromechanical Systems (MEMS). This article covers the basic principles of insect flight and various methods of achieving primitive MAV flight. It is intended for readers who are interested in gaining an overview of insect scaled MAVs as well as for readers interested in extending their individual research to developing MAVs. Discussion in the article is focused on the MAV flight by achieving higher lift than weight for hovering condition. Controllable untethered flight and turn behaviour of insects is not within scope of this article.

In the first section aerodynamics of the insect is briefly described, followed by the desired characteristics of the wings. Later, various methods for the actuator and the transmission are discussed with their strengths and weaknesses. In the last part some insights are provided on the ongoing research and design being carried out by the authors.

2. Aerodynamics

Since the flight aerodynamics is the driving force of the MAV system design, it is crucial to understand aerodynamic forces generated by the insect wings. This description is primarily focused on tethered hovering flight with objective to achieve higher lift than weight. In this section the kinematics of the wings are explained followed by the effects of the kinematic parameters on aerodynamic forces. For the parameter study, wings are assumed to be non flexible. The effect of finite wing stiffness is described in the wing section.



2.1. Kinematics

The insect wing kinematics can be described in 3-DOF system. The system consists of mean stroke plane in which the torsional axis of the wing rotates. The angle of the rotation measured with reference to the axis perpendicular to mean stroke plane, is the *stroke angle* θ . The difference between minimum and maximum stroke angle indicates the stroke amplitude. The angle between wing chord plane and the mean stroke plane is the angle of attack of the wing, also known as *rotational angle* ψ . However, the wing does not flap only in one plane, it rather has a characteristic deviation from the mean stroke plane. The *deviation angle* θ is angle between the instantaneous stroke plane and the mean stroke plane[1]. The angles are shown in Figure 1. This 3-DOF system can be represented by wing tip trajectory as shown in Figure 2. The angle of each of the lines to vertical axis is the angle of attack. The horizontal distance from the vertical center-line is proportional to stroke angle and the vertical displacement of the wing tip is result of the stroke plane deviation.

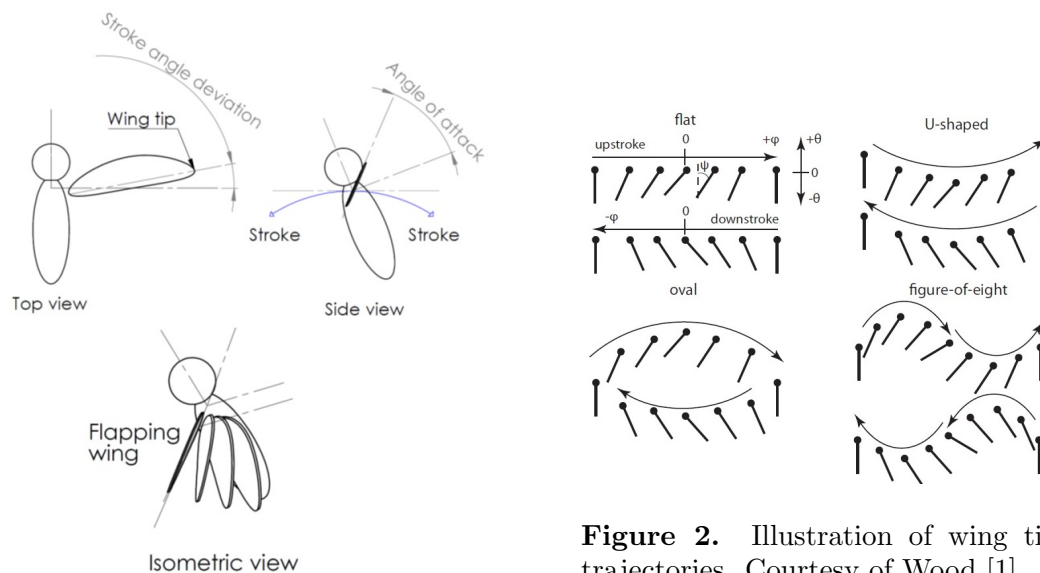


Figure 2. Illustration of wing tip trajectories. Courtesy of Wood [1]

Figure 1. Kinematic degrees of freedom of wing motion.

2.2. Aerodynamic force generation

The forces generated on the wings are primarily governed by three aerodynamic phenomena; dynamic stall, rotational lift and wake capture [2, 3]. When an airfoil is translated through air with an angle of attack, a low pressure vortex is formed at the leading edge which is called as 'leading edge vortex (LEV)'. The LEV at high angle of attack keeps growing until it can no longer stay attached to the airfoil. This separation of airfoil is known as stall, which reduces the lift generation dramatically. Interestingly for the flapping wing motion, the flow stays attached to the wing producing high lift forces at high angle attack. This phenomenon is known as "delayed stall". The "rotational lift" is effect of the wing rotation about its torsional axis at the end of each half-strokes (down-stroke or up-stroke). This maintains the the positive angle of attack and positive lift generation during both half-strokes. At the end of each half stroke when the wing changes its stroke direction, due to the fluid inertia the relative velocity between wing and the fluid is much larger than the absolute velocity of the wing. This higher relative velocity generates large amount of lift at each stroke reversal which is called "wake capture" [2, 3].

2.3. Flight parameter study

In the past two decades, to understand aerodynamic forces produced by the flapping wing, several simulation and experimental studies have been conducted by various scientists. Some of the insect flight parameters are mentioned here, along their effects on the force produced. The lift produced by the wings increases monotonically with the increasing stroke amplitude. Although the power required for the flapping is also increased, the lift-to-power ratio is observed to increase with the stroke amplitude [4] [5]. The angle of attack of the wing is not constant over the half-strokes. The mean angle of attack of $40^\circ - 50^\circ$ is observed to maximize the lift produced and the flight efficiency [4]. Increasing the mean angle of attack increases the drag, and reducing it produces low lift forces [4]. Several insects have been observed with the capability of actively controlling the angle of attack. However the wing rotation is largely aided by the inertial forces at the stroke reversal. This passive mechanism of the wing rotation is studied and utilized by MAV researchers [6] [7]. Sane [4] also shows that the time required by the wing rotation and the point at which the wing rotation starts, affect the aerodynamic forces largely. The short duration of wing rotation time and the rotation occurring before the stroke reversal increase the lift and the aerodynamic efficiency. These parameters need to be considered while designing passive or active wing rotation. The stroke plane deviation alters the instantaneous angle of attack of the wing relative to the fluid flow. Experimental study of the scaled model [4] suggested that the lift and lift-to-drag ratio was reduced with non zero stroke plane deviation. However, insect scale wing suggests the efficiency of the flight might be actually be higher with introduction of stroke plane deviation [1].

Strictly aerodynamically, the higher flapping frequency corresponds to higher wing velocity, increasing the lift and the power consumption. Hence as the frequency increases, the weight capacity of MAV increases, increasing the energy storage capacity. Since the power consumption is increased, the energy requirement for sustained flight also increases. Furthermore, in order to increase the aerodynamic performance, the flapping frequency also needs to satisfy the aerodynamic resonance of the wing motion, which depends on weight and geometry of the wing. Furthermore the actuator also has a high efficiency operating frequency region that needs to be closer to the flapping frequency for an efficient system. Hence, the flapping wing frequency is a complex optimization problem which needs close attention in order to achieve successful insect scale flight [8][4][9][10][5].

3. Wings

Contrary to the previous assumption of the stiff wing, the real insect wings are complex and deformable structures. Some of the insects modulate the wing shape during the flight [3], however in most cases the insect wing deformation is a passive phenomenon. The recent research suggests that the flexibility is necessary and advantageous to flight aerodynamics. Studies have discovered that in some cases the mass of the wing is also not uniform over the wingspan, which improves the aerodynamic force balancing and flight stability [3]. Additionally, wings have been found to have camber in the wing profile, having convex upper surface and concave lower surface. This creates different stiffness values of the wing for upstroke and downstroke, producing different bending and twisting of the wing.

Numerical simulations of the flexible wings suggest that the flexibility improves the lift production, efficiency and other aspects of the wing aerodynamics. The flexible wing enhances the wake capture during the stroke reversal, reducing the drag and in some cases enhancing the lift produced [3]. Computational Fluid Dynamic (CFD) simulation studies for locust and butterflies have respectively revealed 12% and 4% reduction in lift to power ratio due to removal of dynamic wing camber. Whereas the removal of camber and twist cost 35% and 26% lift to power ratio respectively. These studies strongly indicate that the flexibility of the insect wing largely impacts the aerodynamic performance. Additionally the aspect ratio and the geometry

of the wing also affect the lift production and the power consumption.

4. Actuator

There are two configurations of flight muscles found in insects. For direct flight muscles, each wing is connected to a pair of antagonistic muscles which provide power as well as independent control of wings. The indirect flight muscles are connected to an intermediate structure that powers both the wings with a single pair of antagonistic muscles and small muscles are utilized for control. The indirect muscle configuration is found in more evolved species and is also considered to be a superior configuration for reduction in weight and due to good wing synchronization. There are several properties of muscles that need to be satisfied by an artificial actuator such as high energy density, low volume, sufficiently high frequency of operation, high efficiency, high actuator stress-strain. In this section some relevant actuator technologies are mentioned along with their individual strengths and weaknesses.

Ionic polymer metal composite (IPMC): IPMC is an electrochemical actuator where polyelectrolyte is sandwiched between flexible metallic electrodes. Applying voltage across the electrodes produces a bending moment in the actuator. The prime advantage of IPMC is, it operates at low voltage typically less than 5V. Lower voltage has several advantages including simplicity and efficiency of electronics and energy storage. However being an electrochemical actuator the speed of operation is limited by the ion transportation, as well as practical issues such as leakage are present in IPMC.

Piezoelectric: The piezoelectric material is attached to an elastic substrate. When a voltage is applied across it the piezoelectric material changes its shape and dimensions, applying a bending moment on the actuators. The piezoelectric actuator can be used as bending actuator in various configuration viz. unimorph, bimorph [11]. Piezoelectric actuator is a well established actuator with sufficient actuator properties in all the aspects such as energy density, stress-strain, operating voltage etc. However it has complicated manufacturing process and yet not up to the mark of the natural muscle performance.

Dielectric elastomer (DE): An elastic polymer is sandwiched between the compliant electrodes, such that upon application of voltage across the electrodes the attraction between opposite charges generates Maxwell stress in the material. This phenomenon can be utilized to generate linear or bending actuation. Although the large strain and energy density of the DE actuator are very attractive features, the high voltage requirement and the high weight of supporting material is a drawback. The DE actuator shows a large potential to achieve similar or better performance than the natural muscles, and hence chosen for further research and development.

There are several other types of actuators, but those are not considered due to the large difference between design specifications and their properties e.g. shape memory alloy with very low actuation efficiency. Interested readers can read about shape memory alloy, conducting polymer, molecular actuator, thermoelectric Carbon NanoTube (CNT) yarn actuator, CNT electrolytic actuator, electromagnetic actuators MEMS ICE.

5. Transmission

Transmission connects the actuator to the wings of the MAV, converting the actuator movement and force to the desired wing motion. A four-bar mechanism with a pivot point at the base of the wing is the simplest design to provide power to the flapping wings. Several designs have been studied that are suitable for various actuators such as bending type actuator, linear actuator etc.

The dipteran insects are equipped with an additional feature in their transmission known as “click mechanism” [12][13]. This thorax like compliant mechanism stores elastic energy in the flexible hinges to create a bistable system that has stable position at the end of upstroke and downstroke. From start of the half-stroke the hinges store the energy until wing reaches equilibrium point. Beyond the equilibrium, actuator does not need to expend energy, the wing snaps into its stable position using the energy stored in the hinges. This increases the instantaneous velocity of the wings and thereby increasing the lift. The experimental study in [12] found reduced power consumption in the click mechanism compared to the non clicking transmission.

6. Design and Experiments

The authors are currently investigating the field of MAVs in MEMS technology. In this section the design specification and the motivation for those specifications is mentioned. Then the manufacturing of wings and their specifications are also included. The general design target included low cost, low process/manufacturing time. The concept design of the MAV is shown in Figure 3

The Dielectric Elastomer (DE) actuator was chosen for the experimentation due to its high work density, high strain, high frequency operation, ease of manufacturing and low cost. The DE actuator was chosen despite of the requirement of the high voltage. Some studies have reported the possibility of very thin DE or stacking the DE's such that the operating voltage can be reduced to few 100 Volts. Also the DE actuator is a linear actuator and can be designed with the transmission to act as the insect thorax mechanism. Hence, considering the potential development in this technology the DE actuator was chosen for experimentation. The carbon black will be applied on thin silicone film, which will be subjected to high voltage of $\approx 5kV$. The actuator will be used in bow-tie configuration where supporting structure will be made from high stiffness carbon fiber laminate. Along with the actuator, the click mechanism is designed which by the design adds the lift production and efficiency.

The design constraints for the wings were chosen to be very low weight, minimum stiffness corresponding to the insect wing. The 3D printed carbon fiber was chosen for manufacturing of the wing skeleton along Mylar film as wing membrane. The $100\mu m$ thick 3D printed was epoxy glued with $5\mu m$ thick Mylar film as shown in Figure 4. Further investigation of the stiffness properties of the wings is under experimentation and will be compared with the insect wing specifications.

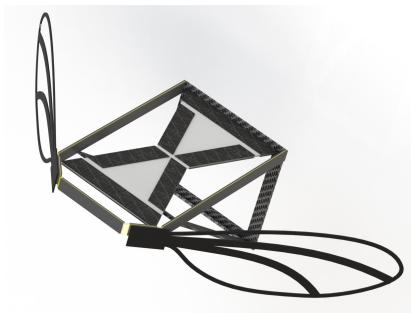


Figure 3. Concept design of the MAV

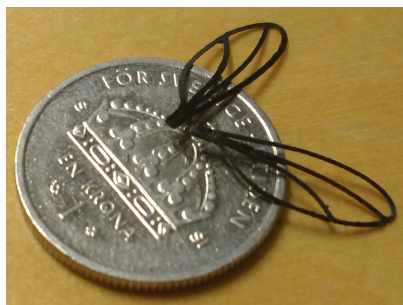


Figure 4. 3D printed wing skeleton

7. Conclusion

The aerodynamic study reveals that the at least 2-DOF wing motion is desired to achieve MAV flight. Stroke amplitude should be maximized and the mean angle of attack close to 45° . The

stroke plane deviation is not mandatory to generate higher lift than weight, but it will improve the MAV's performance. The flapping frequency is a crucial parameter which depends upon and drives several aspects of the MAV design. The insect wing is a complex piece of engineering, but the a very stiff but light wing design is sufficient for the primitive/simple MAV flight.

3D printed carbon fiber shows promising properties and could be a good alternative for manufacturing complicated structure like insect wing. Piezoelectric actuator are proven for MAVs [11]. However, further research on dielectric elastomer could prove them a better choice for MAV actuator. Click mechanism improves lift and efficiency of the flight [12] and will be included in experimentation.

The insect scale flight is fascinating technological challenge and is an excellent project for MEMS research. Achieving the insect scale flight requires multidisciplinary study. Various aspects of the MAV are currently under investigation and the further research on the topic will aid to progress individual technologies such as unsteady aerodynamics, polymer actuators, energy storage etc.

Although Micro Aerial Vehicles is a thorough and complex topic of study, this project aims to prove it is possible to achieve the primitive flight without extensive research in the field. However natural insect capable flight is a very deep and exiting topic which is yet to be fully exploited. The attention from MEMS community will surely help the MAVs to get closer to natural insects.

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