A DESIGNING APPROACH FOR A FLAPPING WING MICRO AIR VEHICLE

1UMANG RAWAT, 2AMIT PAWAR, 3SHASWAT ROY, 4RAJAT SWAMI

1,2,3,4Undergraduate at Delhi, Technological University
Email: Umangrawatdu@gmail.com, Amitnirvana11@gmail.com, Shaswatroy1992@gmail.com, Swami.rajat.22@gmail.com

Abstract: A flapping wing approach has proven to be one of the most successful methods in designing the Micro Air Vehicles (MAVs). These miniature vehicles seek to mimic small birds and insects to achieve never before seen agility in flight. This paper aims at suggestion of flapping mechanisms, wing and frame design and the materials to be used during designing of an ornithopter. Various mechanisms are discussed and improved upon until the final mechanism is obtained which offers unique advantage over the rest in terms of simplicity, weight and drag considerations, frictional losses and symmetric flapping. Analysis on NACA profile chosen for the bird wing is done and few important graphs are plotted and studied. Through this an attempt has been made to provide a roadmap on how to move forward while designing an ornithopter.

I. INTRODUCTION

For many centuries man has been captivated by the flight of birds and insects. They are the masters of agility and remain superior to the conventional, fixed and rotary wing modes of propulsion (Mueller et al., 2010) in terms of maneuverability and other aspects of aerodynamic performance. The motivation behind this work is the interest in flapping wing flight and developing mechanisms to accomplish the required mechanical objectives, which in this case is the flapping motion. The area of flapping wing aerodynamics is relatively new and is continuously growing. Ornithopters can serve as an alternative to propeller driven vehicles. Due to their resemblance with natural fliers and their maneuverability they can be utilized for covert surveillance missions and obtaining geographical information of difficult terrains especially when there is a potential threat to human life. They have also been utilized to keep birds away from airports and the preservation of wildlife. Flapping wing flight is an abstruse area of research mainly because of the unsteady aerodynamics which governs the flapping flight. The desired performance requirements of an ornithopter stems from the features of bird flight such as good maneuverability, low speed flight capability, agility and high propulsive efficiency. Any design of an ornithopter must take into account the same environment as faced by medium to large sized birds i.e unsteady, turbulent and incompressible flow field and Reynolds number >15000.

Ornithopters have been designed to mimic the motion of birds. The actual motion of the wings involves bending, twisting, pitching, flapping and feathering and is hence impossible to recreate. Ornithopters aim at mimicking few aspects of these. Numerous ornithopters have been build such as the Cybird P1 remotely controlled ornithopter, SmartBird and Project Ornithopter. Pioneering work has been done in this field by James DeLaurier. Most of the successful ornithopters involve a simple flapping mechanism with flexible wings. The basis for most is a four bar chain. It consists of a rotating crank connected to a motor. As the crank rotates, the connecting rods push the wings up and down. When a second wing is added and another connecting rod is joined, it produces asymmetric flapping causing the ornithopter to have a tendency to bend more towards one side. To obtain symmetric flapping other mechanisms have been suggested such as the staggered crank, outboard wing hinge, dual cranks and transverse shaft. However the mechanism suggested in this paper offers unique advantage over the rest in terms of simplicity, weight and drag considerations, frictional losses and symmetric flapping.

A membrane type wing was incorporated in the construction of the ornithopter. To relieve the stresses at the highly stressed points, ribs were provided. The wing has the desired torsional and bending flexibility. For our design we have used carbon fibre rods for their exceptional strength-to-weight ratio and polyester sheet, as the wing surface which acts as an aeroelastic surface. The stiffness of the wing is provided by the main spar and the ribs. The wing has a semi-elliptical planform.

II. MATERIALS USED

Frame:
The main frame of an ornithopter is a crucial component. It is essentially used to support all the other elements of the ornithopter like drive mechanism, wings, electronic components, tail mechanism etc. In other mechanical constructions frame is usually designed for strength. But, while designing a frame for an aerial vehicle, it poses certain limitations. Some limitations on the design are as follows:
Strength – Frame must have adequate strength to support all the components and must fulfill its intended purpose.

Weight – In designing an aerial vehicle initial calculations for calculating the lift of the vehicle are directly related to the gross weight of the vehicle. So the frame must be designed for least weight possible without compromising on strength.

Frontal Area – Drag on an aerial vehicle is directly proportional to the frontal area. So, the frame for an aerial vehicle should be as streamlined as possible.

Shape – By designing an ornithopter what we are necessarily doing is imitating the flight of birds. Most applications of an ornithopter require an appearance resembling a bird. Therefore while designing the frame, it is almost mandatory to fabricate it in the shape of a bird.

Cost – Cost is one of the biggest deciding factors in selection of a material. The material used should therefore be cost effective and readily available.

During research for new material for frame we found acrylic. Further research on acrylic was done and following comparison was drawn between acrylic and aluminium:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Yield Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>1.2</td>
<td>114</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.7</td>
<td>40-50</td>
</tr>
</tbody>
</table>

The table provides a clear picture about the superiority of acrylic. An acrylic sheet of 6mm thickness was used for making the frame.

Wing Skeleton:

The material should be chosen such that it has high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. To realize all such needs, Carbon Fiber UD was chosen as the material for wing frame over steel and aluminium. The carbon fiber is used for following reasons:

- Lighter in weight and much stronger than other metals such aluminium, steel or titanium. Hence strength to weight ratio is high.
- The fatigue characteristics are also far superior to other metals.
- It can be produced in more irregular shapes
- Carbon Fiber has a certain natural damping quality. Vibrations are not transmitted through carbon composites with the same fidelity as with metals.
- Corrosion resistant
- Wear resistant
- High thermal insulation properties and low electrical conductivity.

Wing Membrane:

The wing membrane material should be lightweight, flexible and at the same time high shear strength. The material used was polyester (85% by weight of an ester and a dihydric alcohol and a terephthalic acid). It has high strength and resistance against tearing. It is lightweight with a density of 1.3g/cc. It is long lasting, chemically stable and abrasion resistant. It is easily washable. Most importantly it is very cheap and readily available.

III. FRAME

During initial tests the frame was made up of aluminium links held together by small nuts and bolts. The aluminium was selected because of its light weight and cost compared to other metals. The aluminium links were 1.2 cm wide and 1mm thick and of varied lengths. The bolts used were 8 mm in length and 3mm in diameter. We made two single thickness frames which were then connected to each other through cross links 4 cm in length. The maximum length (AB) of the frame was around 30 cm and maximum width (CD) was 10 cm. The approximate total weight of the frame was calculated at 85 gms.
The apparent advantage of this frame was the ample space it provided for mounting other components and its cost. On the other hand the strength of the frame was questionable. Frontal area was large. Furthermore the weight of the frame was quite high. Due to these reasons the frame was withdrawn, replacing it with acrylic as the material with a new design.

There are two approaches in designing the frame, one made up of single flat plate or another with a truss like structure (Jackowski, 2009). The second option was selected because, firstly it will provide easy mounting, secondly the variation of center of mass due to mounting would be reduced and thirdly it will be lighter compared to a single flat plate structure. Therefore a frame of required dimensions was first designed in CATIA V5.

The cross members were specifically provided to support the upper part of the frame and to distribute the load in either sections (upper and lower) of the frame. They will also act as counterweight to the drive mechanism which will be installed in the front part of the frame. This will help in keeping the center of gravity near the middle of the frame and to stabilize the bird horizontally. This drawing was then used to laser cut the final frame as shown.

The dimensions were quite similar to the aluminium frame with maximum length of 29.5 cm and maximum width of 12 cm. The gross weight of the frame was calculated around 50 gms with a weight reduction of around 41%. This justifies the employment of acrylic over aluminium. The supporting members (left) were attached afterwards using a resin based adhesive, to support the main driving shaft. It will be explained in detail in the final assembly drawing.

IV. FLAPPING MECHANISM

Mechanism is one of the most important parameter in modeling of an ornithopter. The first goal of designing a mechanism was to convert in a simple and lightweight fashion, the output of a motor into the sinusoidal oscillation in the range of 3-5 Hz. The second goal was to efficiently couple the rotational drive to the main wing spar for generating the flapping motion. Initially, mechanisms were conceptualized using design software CATIA V5. They were designed and then improved upon, after weighing their pros and cons, which culminated into the final assembly design. All the mechanisms were based on four-bar linkage.

Mechanism I:

This mechanism as shown in the figure employed 3 shafts. The smaller gear in the center is directly coupled with the motor. The bigger gears are meshed on both the sides keeping in mind the utmost accuracy in achieving symmetry of the meshing of gears, as the slightest change in the position of the gears will lead to the failure of the mechanism. The motor drives the central gear, which in turn drives the other 2 gears. The pushrods attached to each gear are thereby attached to the main wing spar. As the central gear rotates, the bigger gears rotate in the opposite direction to the central gear. The trailing edge of the push rods attached to the gears start rotating with it whereas the leading edge attached to the main wing spar produces rocking motion. This overall mechanism results in oscillation of the wing spar, thus conveying the required flapping motion. This mechanism gave precise motion because of presence
of gears, which resulted in lesser friction, noise and vibrations; but on the contrary the frontal area would become too large causing increased drag making it unlikely to be feasible. Also, symmetrical balancing of the weight of the mechanism is not an easy task making it difficult for stability and control.

Mechanism II:

In this mechanism, the gear to the right is coupled with the motor and drives the other gear, imparting rotational motion to the shaft attached to the latter. The wheels are attached on both the ends of the shaft. The shaft rests on two supports attached to the frame, thereby, creating the situation of a simply supported overhanging beam. There are two pushrods attached to each wheels as shown in the figure. The rotation of shaft results in wheel rotation, which subsequently gives rocking motion to the push rods, which in turn imparts flapping motion to the wings. This mechanism had inherent advantages in terms of low frontal drag. It could be easily incorporated into the frame. Though the mechanism was theoretically feasible but did not serve its purpose as a proof of concept. Upon implementation and fabrication of a prototype, it was found that the flapping of both wings was not symmetrical. Also during the experimental run, it was observed that the shaft was bending due to the weight of the wheel at both the ends, which resulted in non-uniform motion and excessive vibration.

Prototype produced using aluminium frame

Mechanism III:

As a result the third mechanism was designed which was sort of an amalgamation of the above two mechanisms. As opposed to the above mechanism, this has 2 cranks at each end of the shaft instead of wheel. The pushrods are connected to both the cranks, connecting the wing spar to the crank. It removed inherent disadvantages of both mechanisms to some extent. The frontal area is minimal, it is compact, simple and at the same time the motion of the wing is symmetrical. It has the least weight of all the mechanisms and is also easy to incorporate in the frame.

V. WING DESIGN

The wings of a flapping wing MAV are one of the most crucial components as it is used for creating lift,
drag and thrust which are prerequisite for any avian flight. Flapping wings are generally constructed using stiff, lightweight rods as structural materials and a thin polymer film which acts as the wing surface. Both wings must have same aeroelastic similarity parameters for them to have similar aerodynamic performance. These parameters include the mass and stiffness distributions. The centre of mass of both wings should be symmetrically located with respect to the frame. Gerdes et al have discussed in detail about the effect of spar configuration on wing performance and have shown that the spar configurations achieving large and stable deformed volume during the flapping cycle give the best combination of lift and thrust.

Induced drag is produced by wingtip vortices and is the drag due to the lift. When the wing moves through air, it gently forces the air downwards. This creates a pressure difference between the air on upper wing surface and the air on lower wing surface causing the air to flow from the lower surface wing root to the upper surface wing root around the wingtip. The spanwise and chordwise flowing air combine with each other and change the velocity of the airflow (both speed and direction) causing it to distort. The wingtip vortices formed towards the trailing edge of the wing decreases the lift generating ability of the wing and deflect the air behind the wing downwards, producing downwash. To compensate this, the angle of attack is increased which tilts the total aerodynamic force backwards and increases drag component. Higher angle of attack leads to increased lift but at the same time increases the induced drag. The angle of attack of the wing should be less than critical angle (generally, 15°) as there are possibilities of stalling of the vehicle at an angle of attack more than the critical angle. Below the critical angle of attack, as the angle of attack increases, the coefficient of lift \(C_L\) increases. At the same time, above the critical angle of attack, as angle of attack increases, the air begins to flow less smoothly over the upper surface of the airfoil and begins to separate from the upper surface resulting in stalling.

In order to create an effective ornithopter, it had to be able to flap its wings to generate enough power to get off the ground and travel through the air.

Flapping wings increase drag and are not as efficient as propeller-powered aircraft. To increase efficiency of the ornithopter, more power is required on the down stroke than on the upstroke. If the wing on the ornithopter was not flexible and flapped at the same angle while moving up and down, it would act like a huge board moving in two dimensions, not producing lift or thrust.

The wing was designed using the standard equations:

\[
L = \frac{1}{2} \rho V^2 S C_L; \]

\[
D = \frac{1}{2} \rho V^2 S C_D; \]

Where, \(\rho\) is the density of air (in kg/m\(^3\)), \(V\) = velocity of air (in m/s), \(S\) = projected area (m\(^2\)), \(C_L\) and \(C_D\) are coefficient of lift and drag, respectively. The critical area was calculated by equating the lift and weight and the following wing was designed

![An Ornithopter Wing](image)

Following table shows the lengths of the different parts of the wing as shown in the above figure:

<table>
<thead>
<tr>
<th>Side</th>
<th>Length (in m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.5</td>
</tr>
<tr>
<td>b</td>
<td>0.2</td>
</tr>
<tr>
<td>c</td>
<td>0.19</td>
</tr>
<tr>
<td>d</td>
<td>0.18</td>
</tr>
<tr>
<td>e</td>
<td>0.16</td>
</tr>
<tr>
<td>f</td>
<td>0.11</td>
</tr>
</tbody>
</table>

This proposed wing skeletal design has a rectangular support structure, which is made up of carbon fiber. The main spar connects the supporting rods, which are perpendicular to it. The length of therods decreases along the leading edge of the main wing spar. The carbon fiber being light in weight exhibits greater flexibility while flapping, more than aluminium or steel, thus helping in a stable flight.

Once the overall structure of the wing was decided, airfoil was selected. The most appropriate airfoil for an ornithopter is one that is suitable for low and medium Reynolds number flight and is relatively insensitive to errors in angle of attack. In order to improve efficiency, a high lift to drag ratio is favored. The spar is also responsible for providing the wing’s required high bending stiffness. Thus, a good candidate spar would be a thin, open section with a high second moment of area and a relatively simple and compact geometry to limit construction difficulties and ensure compatibility with the thickness of the airfoil. Finally, the selected airfoil

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should be thick enough to accommodate torsionally compliant structural members. Thus, the NACA 4412 airfoil was chosen.

**Geometry of NACA 4412**

**Analysis:**

Analysis of the flow around the airfoil was carried out. Angle of attack of the bird wing was taken to be $8^\circ$. The density of air was taken at 60m above sea level to be 1.215 kg/m$^3$. The Reynolds Number (Re) is taken as 15000.

**Streaklines around the airfoil**

The following figure shows the plot between Coefficient of Lift ($C_L$) and Coefficient of Drag ($C_D$). The significance of this plot is that it gives the Lift to Drag ratio (L/D) at various angle of attacks ($\alpha$). A greater L/D ratio is favourable in aircraft design. The graph was plotted at a constant Re = 15000 and for $\alpha$ from 0$^\circ$ to 10$^\circ$. It is seen that best L/D ratio occurs at around $8^\circ$ ($C_L/C_D = 26.22$).

This pressure distribution is in simple terms the pressure at all points around an airfoil. Graph is plotted between negative $C_P$ and length as fraction of the camber length therefore, negative numbers are higher on the graph, as the $C_P$ for the upper surface of the airfoil will be much less than the lower surface. Hence the top line specifies the pressure distribution on the upper surface. This is an important plot for calculation of lift. The total lift can be calculated by integrating the coefficient of pressure ($C_P$) over the wing surface.

**CONCLUSION**

In this paper we have discussed various aspects of designing an ornithopter. Parts of ornithopter like frame, flapping mechanism and wing design have been discussed in detail. Literature survey was done to understand the intricacies of flapping wing flight. The basic understanding about the flapping wing flight of birds was then applied in designing of an ornithopter. Important issues regarding the design criteria for various parts of an ornithopter have been presented. Various alternatives were first designed using a suitable design software and there features were reviewed. Suitable improvements in design were implemented afterwards. Three flapping mechanisms have been suggested and each one has its own characteristics. We have also discussed the complexities of wing design. A semi-elliptical plan form has been proposed because of lower induced drag related to this configuration. Carbon fiber has been recommended for wing skeleton after studying its mechanical properties while polyester has been advocated, for wing membrane. We have also investigated about NACA 4412 airfoil and its viability for ornithopters. Analysis on the airfoil was carried out using JavaFoil. It is a simple lightweight program for studying airfoil characteristics.

Through this an attempt has been made to provide a roadmap on how to move forward while designing an ornithopter.

**REFERENCES**


