Conceptual Design And Practical Recourse Of A Flapping Wing Micro Air Vehicle (MAV)

Umer Yousaf[1], Nadeem Shafi Khan[2]

CAE, NUST, PAKISTAN

ABSTRACT

The design of fixed wing aircraft is not as complex as the design of the flapping wing. In the flapping wing case, there are additional structural limits due to the extensive vibrations produced in spite of the fact that flapping wing provides elevated aerodynamic performance, maneuverability and hover capabilities. This paper presents a conceptual design of a flapping wing aircraft. Five different design considerations, which are essential for fabricating a flapping wing aircraft i.e. power system, gearbox, wings, aerodynamics and controls (and stability) are discussed. The power system including the rubber band, motors and batteries are evaluated in detail. Different types of available power systems along with their pros and cons are enumerated. The details of the wing and accompanying aerodynamics, which are the more essential considerations, are appraised with the help of figures and equations. The design of flapping wing mechanism for use in general studies involving flapping flight and laboratory based experimental optimization of flapping trajectories is also presented. The results emerging from different sources are finally deliberated in the paper.

1. INTRODUCTION

It was the desire of the human being to fly like birds; to complete their flying desire human being constructed airplanes. After making fixed wing aircrafts, the flapping wing concept came and researchers in aeronautics started taking interest in aircrafts with flapping wing. Flapping-wing aircrafts have better aerodynamic performance, maneuverability and hover capabilities and due to these capabilities the flapping wing aircrafts have considerable advantage over fixed wing aircrafts (Mathew, 2003). The aircraft that flies by means of flapping wing is known as ornithopter.

The nomenclature of the different terms used in the paper is given in the following table.
2. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>Aspect ratio</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of attack</td>
</tr>
<tr>
<td>b</td>
<td>Chord length</td>
</tr>
<tr>
<td>c</td>
<td>Lift</td>
</tr>
<tr>
<td>C_L</td>
<td>Lift coefficient</td>
</tr>
<tr>
<td>C_D</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>D_aero</td>
<td>Total aerodynamic drag</td>
</tr>
<tr>
<td>D_ind</td>
<td>Induced drag</td>
</tr>
<tr>
<td>D_par</td>
<td>Parasite drag</td>
</tr>
<tr>
<td>D_pro</td>
<td>Profile drag</td>
</tr>
<tr>
<td>D_w</td>
<td>Drag on a finite wing</td>
</tr>
<tr>
<td>S</td>
<td>Wing area</td>
</tr>
<tr>
<td>U_ref</td>
<td>Reference velocity</td>
</tr>
<tr>
<td>β</td>
<td>Flapping angle</td>
</tr>
<tr>
<td>β_max</td>
<td>Maximum flapping angle</td>
</tr>
<tr>
<td>β_p</td>
<td>Stroke plane angle</td>
</tr>
<tr>
<td>dD_d</td>
<td>Sectional total drag</td>
</tr>
<tr>
<td>dD_f</td>
<td>Sectional friction drag</td>
</tr>
<tr>
<td>dD_p</td>
<td>Sectional profile drag</td>
</tr>
<tr>
<td>dD_i</td>
<td>Sectional induced drag</td>
</tr>
<tr>
<td>dN_c</td>
<td>Sectional circulatory normal force component</td>
</tr>
<tr>
<td>dN_nc</td>
<td>Sectional apparent mass effect</td>
</tr>
</tbody>
</table>

3. BACKGROUND

Birds and insects have evolved to fly with flapping wings while planes are designed to fly with fixed wings. These different styles of flight result from the complex evolutionary history of animals and machines, and as such cannot be entirely explained by aerodynamics. Flapping flight is more maneuverable than steady flight and also flapping flight is more complicated than flight with fixed wings because of the structural movement and the resulting unsteady fluid dynamics (Shyy et al., 2008).

During 1870's, Alphonse Penaud performed a mechanical flapping wing rubber-powered model ornithopter in France, which was documented and witnessed. Alexander Lippisch also worked on ornithopters. During 1990's The Project Ornithopter engine-powered piloted aircraft was designed which is based on the technology of the Harris/DeLaurier model. One of the first successful attempts to develop bird-like flapping flight was made by DeLaurier. In 2006 Dr James Delaurier and his team at University of Toronto made the flapping bird known as Smart Bird. Figure 1 shows a flapping wing ornithopter known as Smart Bird.
4. DESIGN CONSIDERATIONS

The main purpose of this effort is to present an idea about how to fabricate an ornithopter. Here are few design considerations, which are useful and necessary for designing and fabrication of an ornithopter.

4.1 POWER SYSTEMS:

The simplest ornithopters are powered by rubber band. The function of rubber is that it combines the power of motor and battery. It can produce a large amount of torque, so the rubber-powered ornithopters are easy to design and build. The amount of torque produced by the rubber band is dependent on the quality of the rubber.

Building a successful ornithopter also depends on choosing the right battery and motor. There are different types of motors; two of them are brushed and brushless. The selection of motor is dependent on the type and the specifications of the ornithopter. The power of the battery and the motor is dependent on the flight conditions and the requirements. The weight of the ornithopter is also to be considered while choosing the battery and the motor because the weight of the battery changes the weight of the ornithopter and to lift more weight, essentially more weight will be required. Main drive motor speed controller is also a part of power system, which is used to control the speed of the motors. It converts the PWM control signal into the appropriate waveform to drive the high current brushless motor.

4.2 GEAR DESIGN:

Unless we use a rubber band for power, we'll need to gear down the motor, so that it gives enough torque to flap the wings. In designing the flapping wing aircraft, gearbox can be one of the most challenging parts of the ornithopter to build. There are different types of gear mechanisms; few of them are:
4.2.1 Strut Type Gearbox

This type of gearbox is recommended for **micro-sized ornithopters** because it is very simple. In a strut type gearbox, the gear axles are spaced along a linear rail of strut as shown in figure 2. The strut type gearbox has no bearings and since the large ornithopters require bearings to support the loads, so this type of gearbox is not suitable for large ornithopters.

![Figure 2: Strut Type Gearbox](image)

4.2.2 Plate Type Gearbox

The plate type gearbox is recommended for **larger ornithopters**, because of its compatibility with bearings. It has dual crank mechanisms and is a more complex design. Figure 3 shows a plate type gearbox that consists of two or more plates with spacers between them, with bearings to support the gear axles.

![Figure 3: Plate Type GearBox](image)

4.2.3 Chain Drive:

This type of gearbox is also used for large ornithopters because it reduces the weight of the system by distributing load onto more of the gear teeth.

![Figure 4: Chain Drive Gearbox](image)
4.3 WINGS:

When fabricating ornithopters, an efficient wing design can make the difference between failure and success. This is where we talk about aerodynamics to check where the lift comes from. The wings are the main lifting body, which can make the flight success, so the wing consideration is very important. An effective ornithopter must have the wings, which are capable of generating thrust and the lift to keep the aircraft airborne. Since, there will be drag and the gravitational force (weight) pulling the aircraft backward and downward respectively, so the thrust and lift must overcome the drag and weight.

4.3.1 Geometric Similarities

The concept of geometric similarity can help relate different physical quantities by means of the dimensional argument. If flyers are assumed to be geometrically similar, the weight W, lift L, and mass m for un-accelerated level flight, can be expressed with respect to a characteristic length l as

\[ W = L = mg, \text{ here } L = \text{lift} \]

The wing area S and weight are expressed as

\[ S \sim l^2, \quad W \sim l^3. \]

4.3.1.1 Wing Span

When we are studying the flapping birds or ornithopters, parameters of interest are related to the body mass m of the bird or ornithopter. We can relate the wingspan and mass by using geometric similarity. Liu (2006) suggests that, over a large range of the weight, birds and aircraft basically follow the power law as given below:

\[ l = 1.654m^{1/3} \text{ (for aircraft)}; \quad l = 1.704m^{1/3} \text{ (for birds)}. \]

4.3.1.2 Wing Area

The historical data shows that there is a large variation in the wing area (Norberg, 1990). Greenewalt studied different species of the birds and then categorized the birds into three categories (Greenewalt, 1975). He gave the relationship of the wing area and mass for big birds as:

\[ S \sim m^{0.78} \]

4.3.1.3 Aspect Ratio

The AR is a relation between the wingspan b and the wing area S:
Generally, decreasing AR increases the maneuverability and induced drag tends to decrease with higher AR. Similarly, the lift to drag L/D (glide ratio) increases with increasing AR.

4.3.1.4 Frequency

The frequency by the birds or the ornithopters flaps their wings depends on the size of the ornithopter. The flapping frequency is an important parameter in the ornithopter design. There is an upper limit and lower limit of this frequency. The upper and lower frequency limits means that the body cannot flap the wings with the frequency higher or lower (respectively) than the specified frequency due to structural and power limitations.

In an updated study, Pennycuick (1996) studied different species of the birds and made a detailed analysis of the frequency, leading to the following expression:

$$f = m^{3/8} g^{1/2} b^{23/24} S^{1/3} \rho^{3/8}.$$  

Where

- \( m \) = Mass of the bird (kg)
- \( g \) = Acceleration due to gravity (m/s\(^2\))
- \( b \) = Wingspan (m)
- \( S \) = Wing area (m\(^2\))
- \( \rho \) = Air density (kg/m\(^3\)).

The above equation can be used to predict the wing-beat frequency of species whose mass, wingspan, and wing area is known.

4.4 Drag And Power

Drag is the force generated in the direction opposite to the direction of flight. The total aerodynamic drag is due to the resistance to the motion through the air; here firstly the drag on fixed wings then on the flapping wing will be discussed. The total drag acting on the body can be divided into two categories:

- Induced drag (due to the lift)
- Profile drag (associated with form and friction drag on wings)

There is another drag known as parasite drag which is associated with form and friction drag on non-lifting bodies such as fuselage

$$D_{\text{aero}} = D_{\text{ind}} + D_{\text{pro}} + D_{\text{par}}$$
Power can be defined, as the power required in overcoming the drag. Shyy et al. proposed that power required for steady forward flight can be estimated by multiplying the drag force with the forward velocity ($U_{ref}$) (Shyy et al. 2008)

$$P_{aero} = D_{aero}U_{ref}$$

Besides the components previously introduced, there is another component called the inertial power ($P_{iner}$), which is the power needed to move the wings. The total power ($P_{tot}$) required for flight is the sum of the total aerodynamic power and the inertial power:

$$P_{tot} = P_{aero} + P_{iner} = P_{ind} + P_{pro} + P_{par} + P_{iner}$$

This is only the power required for flight and is not the same as the power input (Goldspink, 1977). The graph between power and speed shows that the common power-speed curve is U-Shaped curve as shown in figure 5. In the beginning, the power decreases with speed till it reaches a minimum value. Further increasing speed leads to higher values of power required.

In the case of the birds and the flapping wing, however, the curve is not the same as the curve for the fixed wings. For birds, the power curve is not necessarily U-shaped. Different researchers in the area of avian (related to birds/flapping) flight have come up with different shapes of the power curve (Alexander, 1997).

### 4.5 Aerodynamics

While flapping, birds systematically twist their wings to produce aerodynamic effects in ways similar to the manner that ailerons on the wings of conventional airplanes operate. During the flapping wing flight, one wing is twisted downward, hence AoA and lift is reduced, while the other wing is twisted upward to increase lift. A bird is able to roll by different degrees of twisting between wings (Dial, 1994). Birds
can also have unpowered flight that is gliding (fly with very little movement of wings) and soaring (maintain height without flapping). The birds and flying insects adjust the camber of their wings according to the environmental conditions. On the same principle, the manmade devices work. The main purpose is to prevent flow separation and enhance lift-to-drag ratio (Harjono et al., 2012). Mueller and Delaurier discussed that flapping wings offer potential advantages in maneuverability and energy savings compared with fixed-wing aircraft, as well as vertical takeoff and landing (Mueller and Delaurier, 2001). The flapping wing can have three distinct motions (figure 6) with respect to three axes as:

- Flapping, which is up and down stroke motion of the wing; it has the largest degree of freedom and produces majority of the power.
- Feathering, which is the pitching motion of wing; it can vary along the span.
- Lead-lag, which is in-plane lateral movement of wing.

Flapping angle changes as sinusoidal function and its rate is given by following equations:

\[
\begin{align*}
\beta(t) &= \beta_{max} \cos 2\pi ft \\
\dot{\beta}(t) &= -2\pi f \beta_{max} \cos 2\pi ft \\
\theta(t) &= \frac{r}{B} \theta_o \cos(2\pi ft + \varphi)
\end{align*}
\]

Where \( \theta_o \) is the maximum pitch angle,
\( \varphi \) is the lag between pitching and flapping angle
\( r \) is the distance along the span of the wing under consideration (figure 7).
We can express the vertical and horizontal components of the velocity as

\[ V_x = U \cos \delta + (0.75 \times c \times \dot{\theta} \times \sin \theta) \]
\[ V_z = U \sin \delta + (-r \times \dot{\beta} \times \cos \beta) + (0.75 \times c \times \dot{\theta} \times \sin \theta) \]

Here in the above equation, 0.75 \( c \dot{\theta} \) is the relative air effect of pitching rate \( \dot{\theta} \), which is manifested, at 75% of the chord length.

The relative velocity and relative angle between two velocity components can be expressed as

\[ V = \sqrt{V_x^2 + V_z^2} \quad \psi = \tan^{-1} \frac{V_z}{V_x} \]

The sectional lift \( dL_c \) can be calculated as:

\[ dL_c = \frac{1}{2} \rho V^2 C_{l-c} \times c \times dr \]

Where

- \( c \) is the chord length and
- \( dr \) is width of the element of wing under consideration.
- \( C_{l-c} = 2\pi C(k) \sin \alpha \) (Coefficient lift due to circulation)

The sectional apparent mass effect acting at mid chord is calculated as:

\[ dN_{nc} = \frac{1}{4} \rho \pi c^2 (\dot{\theta}U + r\ddot{\theta} \cos - 0.5\dot{\theta}) \]

The drag force has two components. These are calculated as

- Profile drag \( dD_p \):
  \[ dD_p = \frac{1}{2} \rho V^2 C_{dp} \times c \times dr \]

- Induced drag \( dD_i \):
  \[ dD_i = \frac{1}{2} \rho V^2 C_{di} \times c \times dr \]

The total section drag is then given as

\[ dD_d = dD_p + dD_i \]

The circulatory lift \( dL_c \), non-circulatory force \( dN_{nc} \) and drag \( dD_d \) for each section of the wing changes its direction at every instant during flapping. These forces in the
vertical and horizontal directions will be resolved into force components perpendicular and parallel to the forward velocity, respectively. The vertical and horizontal components of the forces are calculated on the basis of the various forces acting as shown in figure 8.

The analytical expressions for vertical and horizontal components of the forces are given below:

\[
\begin{align*}
  dF_{\text{ver}} &= dL \cos(\psi) \cos\delta + dN_n \cos(-\theta) \cos\beta \cos\delta + dD_a \sin(\psi) \cos\delta \\
  dF_{\text{hor}} &= dL \sin(\psi) \cos\delta + dN_n \sin(-\theta) \cos\beta \cos\delta + dD_a \cos(\psi) \cos\delta 
\end{align*}
\]

By using the above equations, calculating the vertical and horizontal forces within one cycle and then averaging them gives us an estimate of the total average lift produced and the total average thrust produced. We design our wing, which is the most important part of the ornithopter by calculating the lift and drag so that we can check that the ornithopter will be able to fly, or not.

5. Results Of Laboratory Based Experimental Optimization Of Flapping Trajectories

(Harijono et al., 2012) tells us that the analysis and simulation by splitting the flapping and pitching motion shows that:

- The pitching motion dominantly produces the lift, since the relative airflow effect prevailed along 75% of the chord length.
- The thrust is dominated by flapping motion. The vertical component of relative velocity increases significantly as compared to the horizontal components, which causes the force vector produced by the flapping-pitching motion to be directed towards the horizontal axis (thrust axis).
The flapping motion dominates the drag due to the high relative velocity and high-induced drag.

6. THE FLAPPING MECHANISM:

Flapping mechanism is the mechanism, which is used to convert the rotary motion into an oscillatory motion. This is what makes our device an ornithopter instead of an airplane or helicopter.

(Mueller, 2001) gave few mechanisms along with the equations of the motion of each of the mechanisms:

6.1 Direct actuation

Figure 9 shows the direct actuation mechanism in which the wing is directly attached to the motor. In this mechanism, alternating the input signal does the flapping of wings. The frequency and amplitude are not predefined and can be adjusted in this type of mechanism.

![Figure 9: Direct Actuation](image.png)

The equation of motion is given as:

\[ \theta_w \ddot{\phi} = M_m - F_d \cdot l \]

With

- \( \theta_w \) is the moment of inertia of the wing
- \( M_m \) is motor torque
- \( F_d \) is aerodynamic drag force and
- \( l \) is the characteristic length of the wing.

6.2 Actuation with mechanism

In this arrangement, the mechanism is a four-bar linkage. The amplitude is adjusted with the lengths of the links and is predefined as shown in figure 10. This design doesn’t need an alternating input signal.
The equation of motion for the motor angle is:

$$\theta_m \ddot{\alpha} = M_m - b \cos(\alpha) \cdot F$$

Where \(F\) is the force in the joint c

The equation of motion for the wing angle is:

$$\theta_w \ddot{\varphi} = F_d \cdot l - a \cos(\varphi) \cdot F$$

The equation of motion for the four-bar mechanism is given therefore as:

$$\ddot{\alpha} = \left(\frac{1}{\theta_m + \frac{c \cos(\alpha) \theta_w \cos \varphi}{a \cos(\varphi_0 \sin \alpha)}}\right) \left(M_m - \left(\frac{b \cos \alpha}{a \cos(\varphi_0 \sin \alpha)}\right) \cdot \left[F_d \cdot l - \theta_w \varphi_o \sin(\alpha) \ddot{\alpha}^2\right]\right)$$

### 6.3 Mechanism combined with torsional spring

This assembly is basically the same as concept presented in section 6.2 with a minor difference that there is a torsional spring in the wing (figure 11). The benefit of this mechanism is that the amplitude of the wing is amplified much more than the amplitude of the bar-mechanism. It will probably allow higher amplitude and frequency at smaller motor input and will support the motor.

The equation of motion for the wing angle is given as follows:

$$\theta_w \ddot{\varphi} = k(\beta - \varphi) + F_d \cdot l$$

The equation of motion for four-bar linkage is given as:
\[ \theta_m \ddot{\alpha} = M_m - \left( \frac{b \cos \alpha}{a \cos(-\beta \sin \alpha)} \right) \cdot (k(\beta \sin(\alpha) + \varphi)) \]

7. STABILITY AND CONTROL:

It's pretty easy to stabilize a free-flight ornithopter. To stabilize an ornithopter it is important to ensure that **both the wings are symmetrical**. There are few factors like different wing length, different wing spar size or different membrane tension, which can cause asymmetry. Any asymmetry will cause the ornithopter to tilt to either left or right during flight. The tail, instead of the wings, achieves steering of the ornithopter, since it is easier to implement into the design. When the tail swings left or right, the downward force causes the ornithopter to roll left or right. When the tail rotates about its axis, the force on the tail provides yaw control.

8. CONCLUSION:

In this paper, details regarding conceptual design of the flapping wing ornithopter have been presented. These details and theoretical information would help us in designing and ultimately fabricating a flapping wing Micro Air Vehicle (MAV) which could be used for multiple purposes such as surveillance, security, reconnaissance, etc. Our team of researchers is in the process of creating a ground based fully operational model which will lead us to fully controlled flyable MAV in the next phase of this research.
REFERENCES


