

# FLAPPING WINGS, A THEORETICAL APPROACH

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## Abstract

*Micro air vehicles propelled by flapping wings are gaining interest for certain applications because flapping can provide more agility and maneuverability at low speeds. Flapping wings must deform in certain shapes to produce maximum lift and thrust. Traditional micro air vehicles (MAVs) are miniature versions of full-scale aircraft from which their design principles closely follow. The first step in aircraft design is the development of a conceptual design, where basic specifications and vehicle size are established. Conceptual design methods do not rely on specific knowledge of the propulsion system, vehicle layout and subsystems; these details are addressed later in the design process. Non-traditional MAV designs based on birds or insects are less common and without well-established conceptual design methods. A new figure-of-merit for wing structural-inertial efficiency is proposed and used to quantify the performance of real and artificial insect wings. The impact of these results on future flapping-wing MAV designs is discussed in detail. For flight vehicles operated at the low Reynolds number regime, such as birds, bats, insects, as well as small man-made vehicles, flapping and fixed wings are employed in various ways to generate aerodynamic forces. For flapping wings, the unsteady fluid physics, interacting with wing kinematics and shapes determine the lift generation.*

**Keywords:** *Ornithopter; wing loading; wing shape; strouhal's number, etc.*

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## I. INTRODUCTION

With our desire to understand the capabilities of natural flyers such as birds, bats, and insects, and, lately, with increasing interest in developing the micro air vehicle technologies, substantial research efforts have been made on flapping flight.

Flapping wing vehicles, or ornithopters, have proven difficult to control due to the unsteady flow generated by the high-speed flapping surfaces. To-date, research has focused on computational models from which fixed flapping strokes are optimized. These strokes are then fixed and executed open-loop in practice with flapping speed as the primary control output for climb and descent.

Current flapping wing vehicles rely on moving surfaces adapted from traditional aircraft designs for attitude control. A single tail surface typically provides pitch and directional control and the main wings are not actuated beyond their predetermined flapping stroke, albeit at a controllable flapping frequency. While flapping flight has been successfully demonstrated, existing ornithopter designs do not offer the agility of fixed or rotary wing vehicles. Furthermore, it has been found that motion of the single tail surface found on most ornithopters varies moments about multiple axes, resulting in an inherent flight control coupling that makes attitude control a challenging task despite the low potential for maneuverability. Incorporating attitude control actuation on the moving wings of an ornithopter presents physical and

modeling challenges due to constantly changing forces and inherently non-linear aerodynamics. However, if such actuation were available, highly-maneuverable or even aerobatic ornithopter flight might be realized. Rotorcraft has successfully managed constantly moving blades for over 75 years but their mechanisms are not easily transferred to ornithopter flight. Ornithopter aerodynamic surfaces are large relative to their actuation speed, so the relationships between mechanical actuation and resultant aerodynamic forces are highly dependent on external flow conditions. Given suitable flow sensing and aerodynamic modeling capabilities, real-time ornithopter feedback control could be realized with a more articulated, tunable wing stroke than has been previously utilized.

Flapping wing flight offers new possibilities in terms of actuation over conventional control surfaces such as elevons. With flapping, the main wings create both lift and thrust. Altering aerodynamic properties such as camber on each wing can vary the amount of thrust produced on either side of the vehicle analogous to actuation of the B-2 bomber drag rudder. Since the wings are hinged, it is also possible for an ornithopter to vary its flap angle on either wing, rotating the resulting lift vector of both wings differentially between the two sides. Further, a flapping wing vehicle inherits the ability to vary its dihedral angle in a glide by virtue of its hinged wings as well as its mean flap angle between both wings when in a flapping configuration.

## II.FLAPPING WING MECHANISM IN BIRDS

For hundreds of years, man has been fascinated by the flight of natural creatures. It remains an unsolved mystery of nature. Scientists and engineers seek to replicate what birds can do naturally. As an example, planes must maintain a speed higher than the stall speed in order to successfully land, while birds can actually stall and then, using their tail and body, land softly and precisely.

To understand the complexity of 'natural' flight, it's necessary to understand the biomechanics of these creatures – birds, insects and bats. It's important to study their wing organization, and to understand how a particular part of the wing functions to produce flight. At the same time, the goal is to design an air vehicle that is capable of hovering, and, therefore, useful information can be acquired from studying natural hoverers, such as hummingbirds and insects.

From the beginning, pioneers of aeronautics, researchers and experimenters, such as Casey, Lilienthal, and the Wright brothers, were inspired by nature. Today, the method of applying natural principles to engineering the mechanical system is called bio mimicry. This method requires the integration of biological and engineering research.

- **Morphology of Birds:**

Body and wing geometries and their correlation play an important role in in-flight performance of a bird. As limited by the MAV constraints, this research only considers the small birds. Although study of hummingbirds is popular, the limited scope of information available from research on hummingbirds suggests a more general overview of birds as flying species. Study of birds should help to fill out the knowledge gap that exists in study of hummingbirds.

- **Wing Shape :**

Birds wing shapes differ based on their adaptation to nature. Figure 1 shows different types of wings and wingtips.

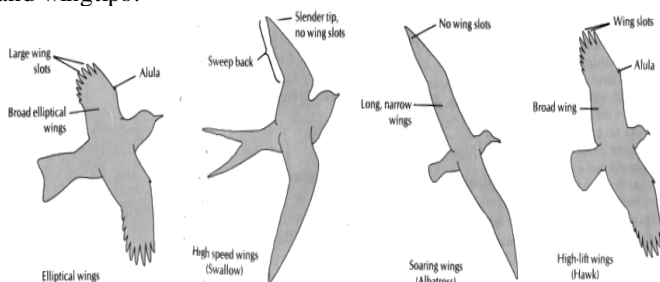


Figure 1: Various wing shapes of birds

In general, wing geometry analysis shows that in adaptation to its surroundings, bird's flight differs. Broad wings allow for efficient power use needed for soaring. Long wings allow for

efficient lift needed for gliding. Pointed wings allow for reduced drag and, therefore, speedy flight. Rounded or elliptical wings allow for better maneuverability. Tapered wings allow for extremely high speed and maneuverability.

- **Aspect Ratio and Wing Loading :**

Wing shape can be described in terms of the aspect ratio. In aerodynamics, the aspect ratio is the wing span squared divided by the wing area, or the wingspan divided by the mean chord as given by

$$A.R = \frac{b^2}{A}$$

$$= \frac{b}{C_{mean}}$$

Here, A.R is the aspect ratio, b is the wing span, A is the wing area, and Cmean is the mean cord.

The aspect ratio by itself is not a very useful parameter unless the wing loading parameter is known. The wing loading is defined as the ratio of the bird's weight to the area of both wings and is expressed as

$$WING\ LOADING = \frac{\text{bird mass}}{\text{wing area}}$$

The larger is the wing loading, the more energy it requires for flying. On the other hand, the lower is the wing loading, the lower is the energy consumption, and, therefore, the lower is the minimum velocity at which the flight is possible. As a result, the wing loading also affects the take-off and landing distances.

Table 1: Wing loading and Aspect ratios of birds

Fliers	Wing-loading	Aspect Ratio
Magnificent Hummingbird	2.52	8.44
Barn Swallow	1.39	7.4
Brown Pelican	5.89	9.8
Homebuilt	54	6
Transport jet	586	~10

- **Variation of the Wing Geometry during Flight – Active Flow Control:**

Birds possess various wing shapes; however, any particular shape has the ability to change during flight as the bird applies active flow control. Birds constantly change wing geometry, including wing shape, wingspan, wing area, twist and so on and their original wing shape, optimizing the flight and energy consumption.

For hummingbirds, variation of the wing geometry is present, however not that drastic as for other species. Figure 2 shows wingspan as a function of flight speed for a variety of birds including hummingbirds. As can be seen from this figure, hummingbirds display the highest span ratio, i.e. they fly with almost straight wings. Also, it can be seen that variation of the wing geometry for hummingbirds is almost independent of speed.

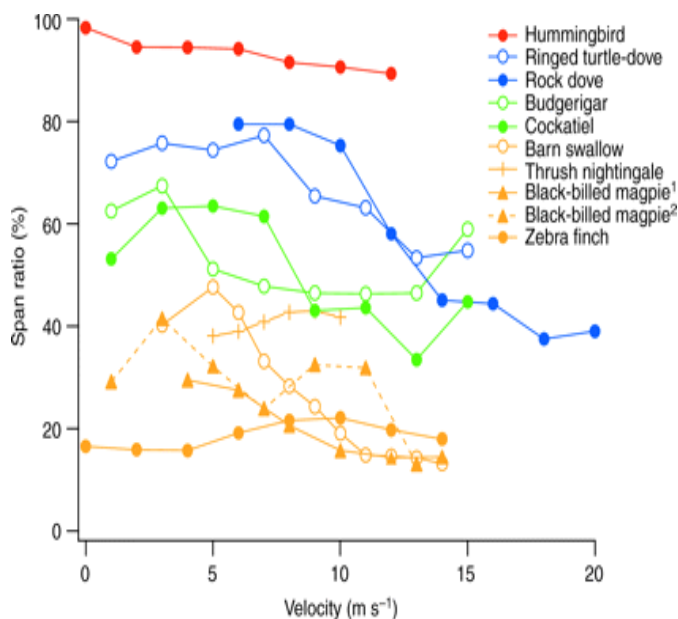


Figure 2: Variation of velocity with span

• **STROUHAL'S NUMBER:**

In dimensional analysis, the Strouhal number (St) is a dimensionless number describing oscillating flow mechanisms. The Strouhal number is an integral part of the fundamentals of fluid mechanics. The Strouhal number is often given as

$$St = \frac{fL}{V},$$

Where 'f' is the frequency of vortex shedding, 'L' is the characteristic length (for example hydraulic diameter) and 'V' is the velocity of the fluid. In certain cases like heaving (plunging) flight, this characteristic length is the amplitude of oscillation.

**II. MICRO AIR VEHICLE-FLAPPING WING**

Flapping wing micro air vehicles (MAVs) are expected to present several advantages over conventional MAVs. Birds and insects are well known for their high degree of maneuverability and quiet flights. Hence, flapping wing MAVs are also expected to be quiet because of low frequency operation, which is suitable for surveillance applications. Flapping

Wing MAVs can also fly at very low forward speed, making them well suited for obstacle avoidance in indoor operations. Several researchers have developed mechanisms to realize the flapping motion and used these mechanisms in MAVs to demonstrate a flapping-wing flight. The main emphasis in these works is on the wing design and the kinematics of the Mechanism.

• **Lift Generation in Flapping Wing Flight:**

To begin to understand flapping wing flight, it is necessary to observe when lift is generated during a flapping cycle. A typical cycle in the flight of a flapping wing vehicle consists of a down stroke and an upstroke. Assuming the wing starts from a maximum height position, at the start of the down stroke, the lift starts to increase. Next is the actual down stroke, where the aerodynamic force peaks. Third is the end of the down stroke, when the lift force starts to decrease. Next is the actual upstroke where aerodynamic forces create negative lift as the wing travels upwards. At the end of the upstroke where negative lift is generated again due to changing wind velocity distributions along the wing's surface.

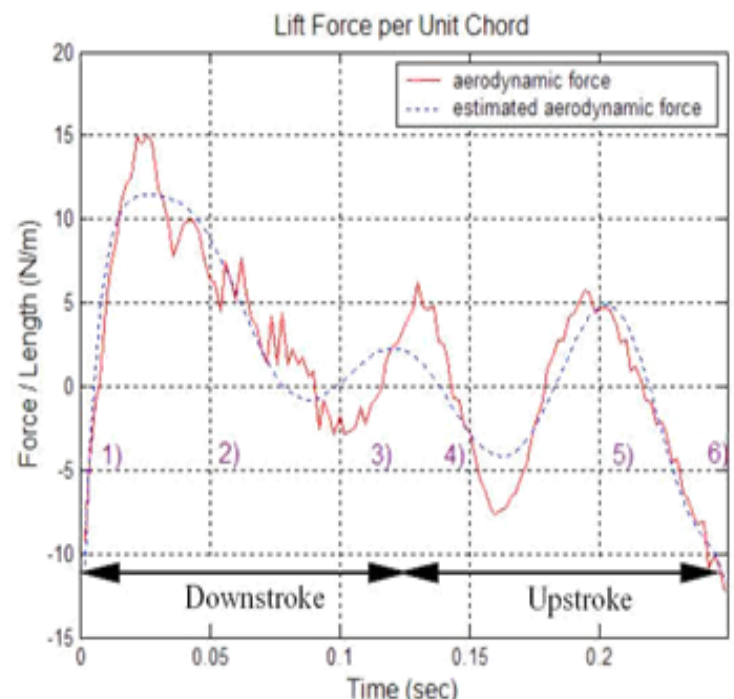


Figure 3: Unit Force vs. Time for Up and Down Strokes

• **Thrust Generation in Flapping Wing Flight:**

In natural flyers, it has been shown that insects take advantage of unsteady Aerodynamic phenomena to generate thrust. The generation of thrust can be broken into 4 parts. First, on the down stroke the wing translates with a fixed collective pitch angle, next near the end of the down stroke, the wing turns so that the blade angle of attack is positive on the upstroke, third is the actual upstroke when the angle of attack is still positive. Fourth is the end of the upstroke/beginning of the down stroke when the wing's angle of attack changes from positive to negative. The lift and thrust generation with respect to the phase of a flapping airfoil. The wing starts at a point, labeled as 18°, and then proceeds to complete one full flap (traveling 360°) and returning to its starting position. From it can be seen that thrust is almost always being generated, but positive lift forces occur primarily on the down stroke movement.

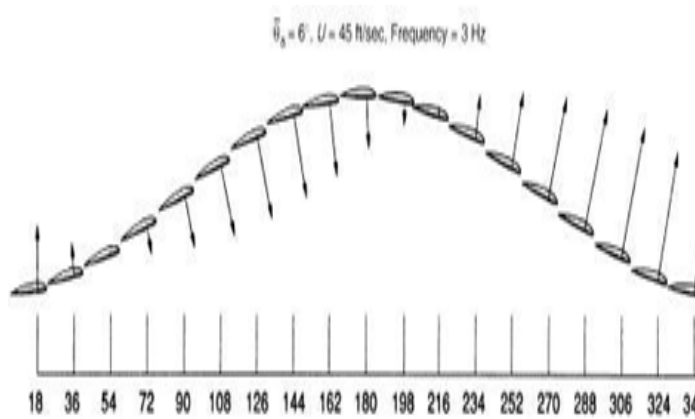


Figure 4: Thrust generation in flapping wing flight

• **Weight Requirements:**

Due to the fact that this mechanism is to simulate a flapping wing aerial robot, it is necessary to be as light weight as possible. Each component and sub-assembly was weighed and an effort was made to choose light-weight materials. The mechanism is built to emulate a larger bird in size, such as a crow. The crow was chosen as a weight and size (wingspan) target. Parts such as motors, bearings and joints constitute a significant amount of weight, so it was necessary to choose materials which had very low cost-to-weight ratios.

• **Flapping Frequency and Speed Requirements:**

Analysis of bird and insect flapping motions show that sustained forward flight can be produced by different flapping motions, and that the motion appropriate for one vehicle or one wing might not be the best for another wing or vehicle. Crows have a flapping frequency of approximately 4 Hz or wing-beats per second. This meant that the target flapping

frequency for the flapping mechanism had to be at least 4 Hz, with the possibility at flapping at a higher frequency being desirable.

**IV.MICRO AIR VEHICLE: DESIGN CONCEPTS:**

• **Concept A: (Double Pushrod Flapping Mechanism)**

This mechanism uses a motor connected to a system of gears that increase flapping force while reducing flapping rate. Pushrods connect to each flapping spar, thus driving the wing motion up and down through pinned connections. Due to the pinned connections, the vertical translation is the only component of motion that is transferred from the drive gear. Since each wing spar has its fulcrum located at a fixed distance  $x$  from the central axis of the mechanism, and the pushrods are of fixed length  $l$ , a problem arises. The two pushrods are never exactly in the same vertical location, except for the apex and the nadir of the flapping motion. This creates a phase lag between the two wings, resulting in slightly asymmetric flapping of the wings. At the miniature size scale, this is an undesirable situation, where control is already difficult due to the low inertia of the fliers relative to their large wing and fin surface area. This style of mechanism is used in the Micro bat, figure, the Chung Hua University MAV, figure, and the University of Delaware ornithopter.

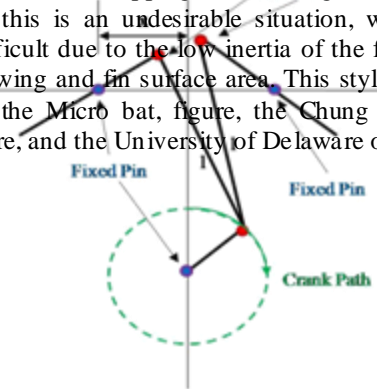
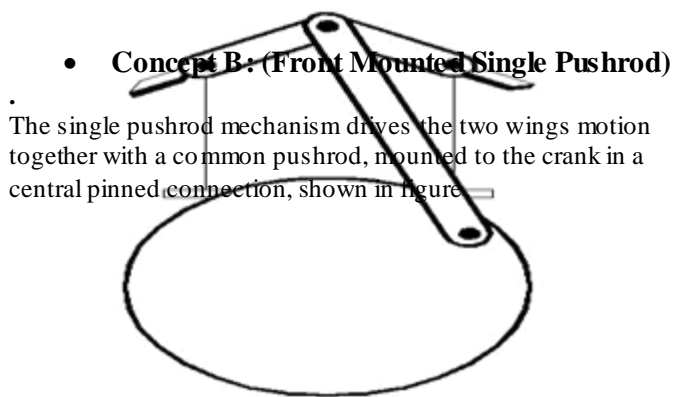


Figure 5: Schematic Double pushrod flapping mechanism

Despite its inherent limitations, this configuration is popular due to its simple construction, light weight, and ease of part replacement. If the MAV is very small and has a sufficiently high flapping rate, it is possible that the asymmetry of the



wings can be masked during the overall flap motion. If the throttle is reduced however, the MAV will begin to exhibit noticeable oscillations and be more difficult to control.



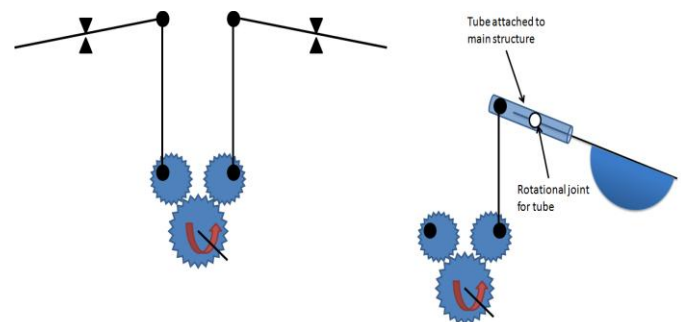
**Figure 6: Single crank functional**

The key difference between the single crank as compared to the double crank is the wing flapping can be made always symmetric, thus improving the low-speed stability of the MAV. A performance tradeoff with this mechanism is that the stresses will be much higher in the single pushrod, since it must drive both wings at the same time, in phase. In addition, the stress on the electronics components including the motor and electronic speed controller will be greater, since the wing flapping is exactly in phase. With the double crank, the wing flapping was slightly out of phase, thus distributing the load of a single flap cycle over a larger time period. While the overall work required is equivalent, the spike in loading is more focused in the single crank mechanism. It is possible to adapt the single crank mechanism to have a phase lag as with the double crank mechanism, by incorporating sliding hinges to support each wing spar. As the wings flap, the hinges that provide a fulcrum for the wings are free to move so that the motion is not jammed up at any point during the flapping motion.

- **Concept C: (Parallel Single Crank)**

This concept is based on the same general structure as concept A, as the given sinusoidal flapping motion does not let much margin for big variations. Anyway the structure presented in figure can also be a good solution. The actuators torque is

transmitted via two gears to the associated wing. The advantage of this concept as a starting point for the further designing is, that each wing can be treated somehow independently of each other in terms of the flapping motion and leaves therefor more space for further ideas to control each wing independently. However the additional gears increase the friction and the complexity and so also the efficiency and the weight respectively. To increase the robustness of the design, the flapping can be actuated according to the right side of figure. Instead of just actuating the wings, a more solid tube, where the wings can be inserted in, is moved. This tube can be attached via a rotational joint to the main structure where also the motor is attached at and gives so more stability to the flapping device



**Figure 7: Schematic drawing of concept of Parallel single crank.**

**CONCLUSION:**

The goal of this thesis was to develop a MAV capable of hovering flight. The focus was also in the improvement in wing design and controllability. This goals were fully reached. The chosen mechanism for turning rotation of the DC-motors into a flapping movement of the wings is accurate and leads to error free functioning. Through more than 300 tests the wings were optimized in angle and chord length and yield to enough lift generation for hover flight. The weight of the MAV is about 14.5g and therefore could be extended by additional hardware such as electronic or batteries or sensors.

In order to achieve more lift generation the search space for finding the optimal wing and mechanical configuration can be extended by a smoother discretization and including also the wing shape. There were no improvements on the motors so far. Many suppliers have the same size of DC-Motors but with different parameters, such as velocity constant. Also there should be a betterment in the controllability by calibrating the motors and reducing play in the structure.

Concluding it can be said that the flapping wing MAV designed and developed in this master thesis is capable of hovering flight. Yet it is not controlled and yields to torque in the pitch and roll axis. The gained knowledge can be used for further improvements and opens the way toward an autonomous flapping wing MAV.

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