A Review on Bio-Inspired Ornithopter

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Abstract— In recent years the subject of flying vehicle propelled by flapping wings, also known as ornithopter, has been an area of interest because of its application to micro aerial vehicles (MAVs). These miniature vehicles seek to mimic small birds and insects to achieve unprecedented agility in flight. This renewed interest has raised a host of new problems in vehicle dynamics and control to explore. Ornithopters are robotic flight vehicles that employ flapping wings to generate lift and thrust forces. This paper elaborates the essential aspects for the development of ornithopter and describes mechanism of operation.

Key words: Flapping Wings, Micro Aerial Vehicles (MAVs), Ornithopter

I. INTRODUCTION

An ornithopter is an aircraft that flies by flapping its wings, i.e. it can also be defined as an aircraft that derives its thrust and lift from the mechanism of flapping wings. Ornithopters imitate nature as no natural creatures have any rotating parts.

The principle of operation of the ornithopter is same as the airplane; the forward motion through the air allows the wings to deflect air downward, producing lift. The flapping motion of the wings takes the place of rotating propeller. Engineers and researchers have experimented with wings that require carbon fiber, plywood, fabric, ribs, and the trailing edge to be stiff, strong, and for the mass to be as low as possible. Unlike airplanes and helicopters, the driving airfoils of the ornithopter have a flapping or oscillating motion, instead of rotary motion. As with helicopters, the wings usually have a combined function of providing both lift and thrust. Theoretically, the flapping wing can be set to zero angle of attack on the upstroke, so it passes easily through the air. Since typically the flapping airfoils produce both lift and thrust, drag – inducing structures are minimized. These two advantages potentially allow a high degree of efficiency.

In propeller or jet driven aircraft, the propeller creates a relatively narrow stream of relatively fast-moving air. The energy carried by the air is lost. The same amount of force can be produced by accelerating a larger mass of air to a smaller velocity, for example by using a larger propeller or adding a bypass fan to a jet engine. Use of flapping wings offers even larger displaced air mass, moved at lower velocity, thus improving efficiency.

Some Practical Benefits of an ornithopter can be enlisted as follows:

1) Flapping wings offer improved efficiency
2) Better maneuverability.
3) Reduced noise compared with the rotary – driven airplanes and helicopters.
4) Resemblance to a real bird enables its use for intelligence and surveillance.

II. ESSENTIAL PARTS OF AN ORNITHOPTER

A. Gear Box:

In ornithopter, gear mechanisms are used to provide sufficient torque to flap the wings. A gear is a rotating machine part having cut teeth, which mesh with another toothed part to transmit torque. Two or more gears working in tandem are called a transmission and can produce a mechanical advantage through a gear ratio and thus may be considered a simple machine. Geared devices can change the speed, magnitude, and direction of a power source. The most common situation is for a gear to mesh with another gear; however, a gear can also mesh a non-rotating toothed part, called a rack, thereby producing translation instead of rotation.

B. Main Body:

In general, the frame of the body of an ornithopter is made of Balsa Wood and Carbon fibers. To minimize the weight of the ornithopter, Styrofoam is stuck in the gap of the body frame, maintaining appropriate sized gaps for placing micro controller board, battery, receiver and servos. A proper mount is attached in front of the body frame for the motor and gear box.

C. Wings:

For an ornithopter to be effective, it should be capable to flap its wings to generate enough power to get off the ground and travel through the air. Efficient flapping of the wing is characterized by pitching angles, lagging plunging displacements by approximately 90 degrees. 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 wings of the ornithopter are not flexible and flapped at the same angle while moving up and down, the ornithopter will act like a huge board moving in two dimensions, not producing lift or thrust. The flexibility and movability of the wings enable their twist and bend to the reactions of the ornithopter while in flight.

D. Tail Wing:

To steer an ornithopter efficiently and perform turns easily, necessary condition is the stabilization of a free flight ornithopter, which depends on its tail. The tail of an ornithopter is generally a V-shaped tail with an angle of 120 degrees. It is made of Balsa Wood or Carbon and Fiber or Plastic sheet is used to cover it. Two stepper or servo motors are mounted on the body frame to move the tail, which changes the direction and pitch of the ornithopter.

III. AERODYNAMIC ASPECTS OF AN ORNITHOPTER

Lift is the force that utilizes the fluid continuity and Newton's Laws to create a force perpendicular to the flow of fluid. Lift is opposed by weight as it is the force that pulls things towards the ground. Thrust is the force that moves things through the air while drag is the aerodynamic force that reduces speed.

The wings of the ornithopter are attached to the body at an angle, which is called the angle of attack; the downward stroke of the wing deflects air downward and backward, generating the lift and thrust. The surface of the wings is designed flexible which causes the wings to flex to required angle of attack to produce the forces essential for achieving flight.

IV. FLIGHT MECHANISM OF ORNITHOPTER

There are four primary classifications of drive mechanisms used by the MAVs are: (1) Double pushrod, (2) Double crank, (3) Single pushrod, (4) Side-mounted crank. Each of these four mechanisms presents a tradeoff of multiple important performance attributes. Some of the considerations for selecting a mechanism layout include the geometry and weight constraints for the MAV, as well as the required forces to be transmitted and the rate of flapping. Other concerns include the manufacturability of the selected design, especially with very small and light MAVs. As the size of mechanisms grows ever-smaller, the human limitation becomes a factor in the construction of more complex mechanism layouts. Due to the reduced stability of MAV platforms, a durable mechanism is desired, due to a variety of damaging factors including dirt contamination, crashes, assembly stresses, and the fatigue effects of high flapping rates.

A. *Front Mounted Double Pushrod*

The first style of mechanism discussed is a front-mounted double pushrod mechanism, shown in figure 1. [2]. 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 and now 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, 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.

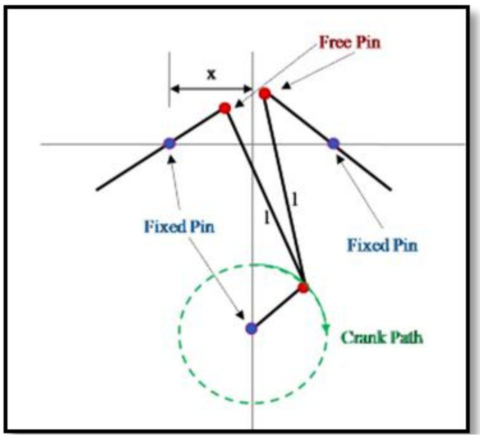


Fig. 1: Double pushrod flapping mechanism [2]

This style of mechanism is used in the Microbat, which is shown in figure 2, the Chung Hua University MAV, figure 3 and the University of Delaware Ornithopter. 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 speed is reduced however, the MAV will begin to exhibit noticeable oscillations and be more difficult to control.

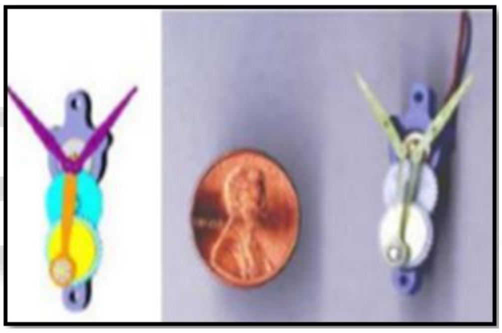
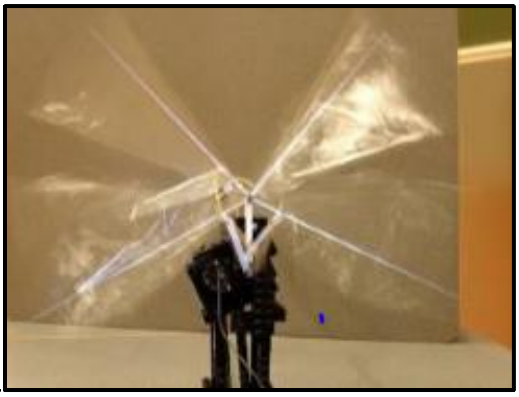


Fig. 2: Double pushrod from Microbat [2]

Fig 3: Chung Hua University MAV double pushrod mechanism

B. *Front Mounted Double Crank*

A variation of the double pushrod design is the double crank. This design is similar in functionality, except that the two pushrods no longer share a common mounting point on the crank. The Delfly uses this style mechanism, shown in figure 4.



Fig, 4: Delfly I front mounted double crank

The benefit of this change is that the asymmetry in wing flapping can be reduced, thus improving the stability of the MAV.

C. Front Mounted Single Pushrod

The single pushrod mechanism drives the two wings' motion together with a common pushrod, mounted to the crank in a central pinned connection, shown in figure 5.

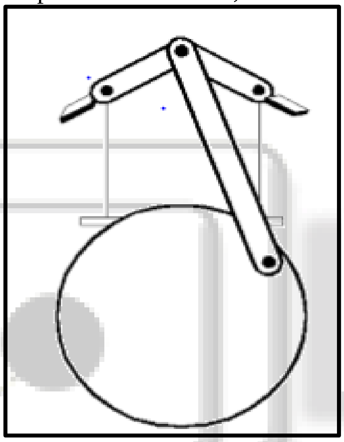


Fig. 5: Single crank functional schematic

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. 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 [2]. 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. As a method of reducing the loading spike, a compliant frame can be used. The general principle of operation is that by incorporating elastic links into the mechanism, spring energy can be stored and released during the flap cycle. By designing the geometry and stiffness of the system to optimize the energy storage and release, the loading range, i.e. the difference between the largest and smallest load can be reduced. Reduction in the loading range has been shown to improve the efficiency of the mechanism, thus prolonging battery life and improving the reliability of the electronics components. A UMD single crank mechanism is shown in figure 6.

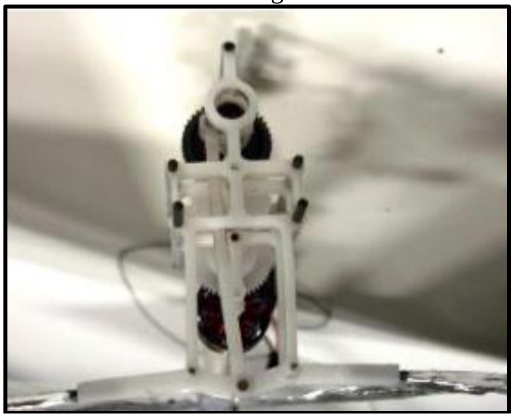


Fig. 6: UMD single crank mechanism

Due to the layout of the mechanism, it is possible for both compliant links in the mechanism to deflect simultaneously in the same direction, a degree of freedom that can be thought of as 'sway'. Causes for the sway effect include driving wings that are too large for the mechanism, driving wings too rapidly, or large wind gusting or other external loads of the mechanism that remove it from its design range. This effect serves to reduce the distance from the pushrod to the pinned connection that drives the wings up and down, thus altering the designed-in flapping range and causing undesired dynamic effects. For these reasons, it is important to ensure the single pushrod is staying within its designed limits. This behavior can be alleviated with the addition of a pin and slider joint in the center of the mechanism, resulting in always symmetric deflections by the compliant links one variation on the single crank mechanism concept is shown in figure 7.

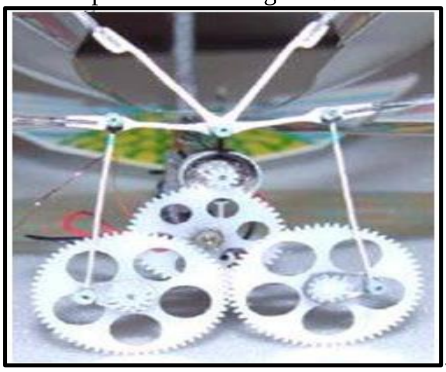


Fig. 7: Parallel single cranks

With a pair of front-mounted single cranks, some of the problems of this mechanism style are solved. The mechanism is set up to flap the wings in phase, with a pair of equally sized cranking gears attached to the drive motor.

D. Side Mounted Crank

Some of the MAVs discussed use another style of single crank mechanism, the sideways pushrod layout. In this configuration, the axis of gear rotation is shifted 90 degrees to be perpendicular to the direction of flight and coincident with the MAV elevation axis. There is one pushrod used to drive each wing in this mechanism layout. Each pushrod is attached to the slowest-moving gear, with one on both the left and right side of the MAV that moves vertically with the gear using a pinned connection. The vertical movement of the pushrods is transmitted to the wing spars at a mounting point, thus driving the wings up and down. In the Delfly II, shown in figure 8 and Delfly Micro, shown in figure 9.

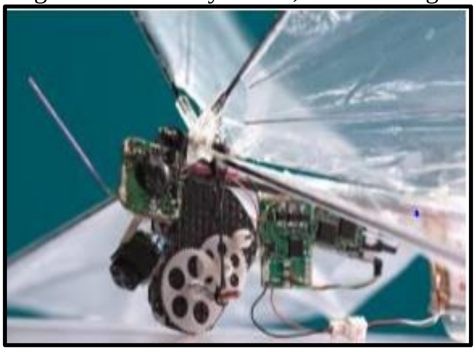


Fig. 8: Delfly II side mounted pushrod mechanism

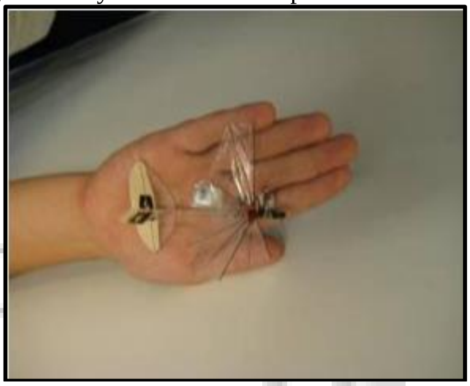


Fig. 9: Delfly Micro side mounted pushrod mechanism

This layout transmits crank motion into the elevation axis, instead of the roll axis. For lighter MAV's or MAV's with a large surface area to weight ratio, this configuration is helpful in maintaining stability and controllability during flights. Construction is more complex than the other two layouts; Exposure to crash damage is also greater when using this configuration. Since the pushrods are exposed on both sides of the MAV, it must be shielded from crash damage in a variety of different directions. If a pushrod were bent in a crash, it would probably need replacement since any small difference between the two sides of the mechanism could cause large stresses to arise during highspeed flapping. If the manufacturing and durability limitations can be overcome, the symmetric flapping, light weight, and compact size make this mechanism a good layout for very small MAVs.

V. THEORETICAL ANALYSIS

A flapping UAV is a flight vehicle which generates aerodynamic forces and moments to fly. The flexibility of wings contributes to gaining sufficient lift and thrust. Even for the design of small flapping UAV, there are too many design parameters including wing geometry, wing kinematics, and wing structural dynamics. It is not yet clear of each parameter's effects in the total aerodynamics of a model. Commercially available toy flappers can barely fly and it is difficult for them to carry additional payloads, such as cameras and chemical sensors. Giving them, a payload instantly changes their behavior. From a research paper [3], we found that when it was installed additional mass (5% of the entire system mass) onto a toy flapper at the center of gravity so that the flapper's longitudinal dynamics were changed as little as possible. Then, with the wing area was gradually increased until the modified flappers could fly.

However, those modified flappers proved ineffective, because when the wing area was enlarged, much higher torque and power were required. Moreover, the wing is not rigid, so structural properties such as mode shapes and natural frequencies should be tuned for an enlarged wing. The main fundamental forces those are needed to be balanced must for the flight. Four force acts directly on a flying model, as shown in figure 10. These are lift force, drag force, thrust force and weight of the bird. Thrust and drag cancels each other and same thing goes for lift and weight when the model is in cruising flight.

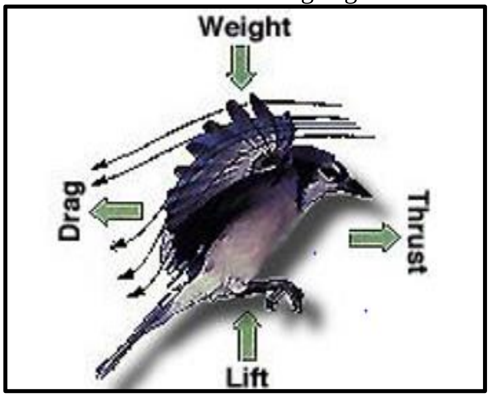


Fig. 10: Four main forces acting on a bird

Lift is the function of the air density, the square of the velocity, the air's viscosity and compressibility, the surface area over which the air flows, the body shape, and the wing angle to the flow. Importantly the lift must be equal of more than the total weight of the bird. Efficient lift generation mostly depends on the wing design. Wing is responsible for the maneuverability of the system. Its aspect ratio, angle of attack, wing loading all these terms are related to gain the efficiency in flight. The cross section of a bird's wing is known as ― airfoil shaped and the airfoil shape mainly describes how lift force is generated. From bird's wing, we found that the wings are shaped in such a way that the distance from the front to back over the top of the wing is greater than the distance measured under the wing. That means the wing is curved in width at an angle inside of it. But through the length, it is straight when the wing is stretched in the air. This curvature is the main formula of the lift generation, which was found from ― Bernoulli's theorem. For the same amount of air to pass over the longer distance on top, the air flows much faster over the top and slower over the bottom as the distance is lower there. To avoid the mathematical complexity of the velocity distribution and pressure distributions on the airfoil surface because of the airflow, we are simply saying that the airfoil gains a large lift force for an inclination angle below the critical angle of attack.

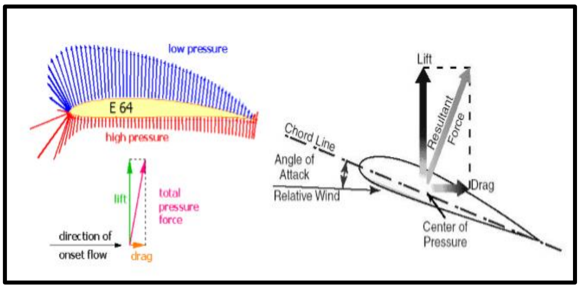


Fig. 11: Lift generation technique of a typical airfoil

Not only airfoil is important to generate sufficient lift force to fly a bird but also there are some variables that are responsible. These are wing size, airspeed, air density, or angle of attack of the airfoil. To get the general equation of the light. The relation between wing size (we call it wing surfaces) and lift L is

A. Lift ∝ Wing surface area

The relationship between lift and airspeed is less straight forward. We need to find first the amount of airflow around the wing first. The mass flow of air around the wing first. The mass flow of air around a wing is proportional to the airspeed V times the air density d. Now using Newton's 2nd law of motion, we can find the force caused by airflow and that is V.d.V or dV^2. Since bird's wings must support its weight against the gravitational force lift must be equal the weight W. So, the final relationship becomes,

$$W = 0.3\times dV^2\times S$$

Here 0.3 is the constant related to the angle of attack for cruise flight. Its average value is 6°. If we modify the equation like below,

$$W = 0.3\times dV^2 \tag{5.1}$$

We find the wing loading. Here W/S is the wing loading from which we can understand that higher the wing loading, faster the bird must fly to overcome its weight force (gravity). That is why, a Boeing 747 flying with a higher wing loading and take-off speed is much higher to generate take-off lift force.

When a wing moves through still air, the air exerts a force to the wing. If the wing is parallel with the air threads then the force is entirely a drag force. But if an inclination angle is kept. we can get a lift force from the wing. This phenomenon can be described wing the following diagram.

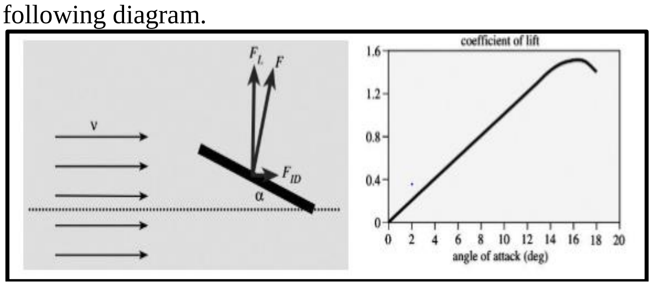


Fig. 12: Wing's angle of attack contributes in lift generation

For an angle of attack that is greater than 0° and less than 15°, we get a lift force component F_L at the right angle of the air flow lines. For efficient wing design, the angle is not exactly the right angle, but it is inclined forwards with respect to the wing chord. At higher angles of attack, air flow over the top of the wing detaches and the wing stalls. The forward component of lift is important to produce a thrust component for the bird. At a given angle there will be so much lift and so much drag. By dividing the lift by the drag, the lift to drag ratio is obtained. As lift and drag change with angle, the lift to drag ratio will also change. There will be an angle at which the lift to drag ratio is largest, where we will get the greatest lift, for the least amount of drag. It is essential to make the wing operate at this angle throughout most of the stroke. By doing it we can guarantee that for drag being counteracted, we are getting the greatest lift possible.

J. Oliver Linton used the formula of lift force F_L in his paper is

$$F_L=\frac{1}{2}\times C_L\times S\times\rho\times V^2 \tag{5.2}$$

Where,
S=Area of the wing
ρ=Density of air
V=velocity of wing
C_L=Lift co-efficient and critically varies with angle of attack and

$$C_L= k_L\times\alpha \tag{5.3}$$

k_L is approximately equal to 5 and α measured in radians.
Finally, the mean lift force from his became,

$$\text{Mean Lift} = \frac{1}{4}\times k_L\times\beta\times S\times\rho\times V^2 \tag{5.4}$$

As J Oliver described that bird wings don't contribute neither on lift nor thrust during the upstroke.

Note: β represents angle of attack, S is the wing area, ρ is density of air and V is the wing speed through the air. The standard value of air density was taken 1.3kg/m³. The equation of β in term of bird's mass is

$$\beta=\frac{4\times M\times g}{k_l\times S\times\rho\times V^2} \tag{5.5}$$

Here M is the bird's mass; g stands for gravitational acceleration and R_g is the glide ratio.
The formula of thrust generation is,

$$\text{Mean thrust}=\frac{1}{6}\times k_L\times S\times\rho\times\sigma^2\times V^2 \tag{5.6}$$

Here, σ = Strouhal Number. For cruising flight value is 0.2.
The power equation is simply (thrust × speed).
Therefore,

$$\text{Power}=\frac{1}{6}\times k_L\times S\times\rho\times\sigma^2\times V^3 \tag{5.7}$$

Note: A= wing flapping amplitude,
f = wing flapping frequency;
Rest of the variables hold their previous meanings.

For the ornithopter to fly vertically indefinitely, it has to produce more thrust than its weight. The thrust must counteract the weight of the ornithopter and whatever thrust is left counteracts the drag while it's moving vertically. To achieve this, the wings must move as quickly as possible with the least resistance. The more resistance there is, the more the motor slows down and the less lift the wings produce. This is done by making the angle the wing sweeps across as large as it can be. This increases the speed of the wing while minimizing its acceleration. The force required to accelerate a wing to an oscillation increases with the square of the frequency and it changes linearly with amplitude. Lift on the other hand increases with the square of the speed, and the speed increases linearly with both frequency and amplitude. This means that by doubling the frequency, the lift quadruples, yet the force required to accelerate it also quadruples. If we double the amplitude, the velocity will double, and as such the lift will quadruple, yet the force required accelerating only doubles. This means that we can achieve the same lift for half the resistance by increasing amplitude instead of frequency.

VI. Conclusion

Ornithopters have been a relatively obscure area of research in comparison to fixed wing aircraft and field of ornithopter design is sparsely populated. Much of the research done has been performed by hobbyists such as Sean Kinkade. In this paper, the case for the construction of a large scale ornithopter suitable for control systems research and surveillance application is motivated. Performance and weight constraints imposed by the computers and sensors desired onboard make it difficult to work with the smaller platforms currently available, let alone micro UAVs currently in development. The ornithopter was designed from the ground up with the needs of research in mind. All components have been designed to be as lightweight and high performance as possible to maximize payload capacity and are intended to fail in predictable and repairable ways. Examples of this are the screw in wing spars and replaceable face plates. In addition to this all parts of the ornithopter are simple and inexpensive to fabricate and assemble. Manual and initial autonomous flight tests have been conducted and show that the ornithopter is capable of sustained flight with a full load of electronics and can be stabilized by simple controllers. At the base is the mechanical ornithopter system which has the main requirement of flying acceptably. Acceptable in this most preliminary case is to sustain weight of the sensors and computer. Branching out from this base requirement are several secondary requirements. Because this is a controls research platform it can be expected that the ornithopter will end most of its beginning stages, this makes crash survivability of great importance in addition to it being a reliable machine in less severe conditions. An emphasis is placed on designed points of failure to isolate damage to parts easily replaced in the field. In addition to this all the systems need to be easy to tie into the computer controller.

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