Construction of a Moth-inspired Ornithopter

Terence A. Southard

Case Western Reserve University

Department of Physics, Department of Mechanical and Aerospace Engineering

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Abstract

An ornithopter is an aircraft that creates both lift and thrust through the motion of flapping wings. In this project, the aim is to design and create an ornithopter scaled similar to the tobacco horn worm moth with Professor Roger Quinn’s biorobotics research group. The initial prototype will be simplified to have just two wings. Many different designs for such vehicles exist, and most are biologically inspired.

Thus, as a first attempt to create a working ornithopter, I will begin by reproducing a simple, rubber band powered ornithopter. Second, I will combine design elements from existing sources to create a battery-powered ornithopter with an on-board power supply and motor.

The primary inspiration for the final product will be DelFly, produced by a team at Delft University of Technology. The ultimate goal will be to then incorporate radio control into the design, resulting in a controllable air vehicle.

Background

To begin a discussion about ornithopters, I first would like to discuss steady-state airfoils. These airfoils are normally found on fixed-wing aircraft, which are not much like ornithopters. However, this will be a convenient place to begin our analysis. In order to explain aerodynamic forces on this type of wing, we can use three different tools: First, we can consider the pressure acting on all surfaces of the wing. Second, we can consider the momentum transfer that the
wing imparts on the surrounding fluid – This is, at its heart, simply applying Newton’s Third Law. Finally, we can consider the vorticity that the wing creates in the surrounding flow – If the wing tends to turn the flow downwards then it will produce lift. Airfoil analysis is most conveniently done in the wing’s reference frame, so I will define all airflows as being relative to the wing. For flapping wings, this means I will see an incoming flow velocity component due to the airfoil’s motion. I will also define the “angle of attack” as the angle between the wing’s chord and the incoming airflow.

From here I will define the lift force $L$ as being the component of the net aerodynamic force that is perpendicular to the incoming airflow. I will also define the drag force $D$ as being the component of this force parallel to the incoming flow.

This allows me to define two dimensionless parameters, the lift coefficient $C_L$ and drag coefficient $C_D$ ($L$ and $D$ are the Lift and Drag forces, $\rho$ is the fluid density, $v$ is the relative flow velocity, and $S$ is the wing planform area):

$$C_L = \frac{L}{\frac{1}{2}\rho v^2 S} \quad \quad C_D = \frac{D}{\frac{1}{2}\rho v^2 S}$$
Now we can analyze how the Lift and Drag coefficients typically vary with angle of attack. These relationships will be different for every airfoil, but also follow certain trends. The Lift coefficient has a portion that is linear, lower angles of attack, and a portion that falls off at higher angles of attack. The linear portion has a slope approximately $2\pi$, by thin airfoil theory, and corresponds to flight where the flow sticks to all surfaces of the wing. As the angle of attack increases, the wing increases its displacement of the airflow, which increases lift. However, at some point increasing the angle of attack begins to separate the flow – the fluid’s inertia does not allow it to curve so drastically around the wing, and we begin to see the slope $dC_L/d\alpha$ decrease. At the lift coefficient’s maximum value, we have the critical angle of attack – at higher angles of attack, the airfoil begins to produce less lift. This is called a stall and occurs due to flow separation. The drag coefficient is nearly quadratic with angle of attack.

Diagram showing typical $C_L$ and $C_D$ values with angle of attack
As previously stated, ornithopter wings follow a slightly different set of rules. Ornithopter wings constantly change the angle of attack due to the flapping motion, and are therefore not in steady-state like the aforementioned airfoils. Also, since the wing’s flapping velocity is often high relative to the flight velocity, drag on the airfoil points more vertically than backwards. Because of this, ornithopter flight is not broken by resultant stalls, but instead amplified.
Secondly, since the wings are actuated from the leading edge, the trailing edge lags behind. This creates a twisting motion in flight, and allows the wing to push the air backwards with each stroke. This is effectively thrust.

Third, I will introduce a dynamic stall, which is a phenomenon that is observed when an airfoil changes its angle of attack quickly. The fluid’s inertia does not allow it to “keep up” with the wing, which creates a low pressure region in the flow. The low pressure region creates a leading edge vortex which propagates down the surface of the wing. This momentarily increases the lift and drag of the airfoil, which helps the vehicle fly.

![Illustration of a Dynamic Stall showing how the leading edge vortex propagates](image)
Finally, ornithopters should execute a maneuver called the “clap and fling”. In this, the wings touch together, expelling the air between them. When they pull apart, there is a “sucking” action, increasing the leading edge vortex strength and the thrust.

![Illustration of the Clap and Fling technique (1)](image)

**Purpose**

Professor Roger Quinn studies biologically-inspired robotics. His lab’s designs include insect-like robots with walking legs, robots with hybrid walking-rolling “whegs”, and flexible fixed-wing air vehicles. As a project related to aerodynamics, Professor Quinn and I determined that it would be mutually beneficial for me to develop an ornithopter, combining his specialization in biorobotics and my interest in exploring flight mechanics. Scaled similarly to the Tobacco Hornworm Moth, we designed this vehicle to have a wingspan of about 20cm and a flapping
frequency on the order of 20 Hz. Once finally constructed, Professor Quinn will take the final product and use it in research regarding insect flight.

From this project, I was given the opportunity to further my understanding of aerodynamics and also explore engineering design and fabrication methods in a laboratory setting. This project has also helped me learn about the logistics and process of designing and constructing a robot.

**Objectives**

The final goal was to ultimately produce an ornithopter micro-air-vehicle (MAV) with onboard motor and power supply as well as radio control to adjust motor speed and trigger aerodynamic control surfaces. This will be somewhat like DelFly from Delft University – creating a similar ornithopter was Professor Quinn’s initial motivation.

On the path to achieving this goal, I decided to start by constructing a “homemade project“-type ornithopter. This design involved a balsa wood construction, a twisted rubber band power source, and a tissue paper wing. This design, despite being very simple and low-tech, served as a good starting point and learning endeavor. I learned from this device that a successful ornithopter will ideally have wings that flap in phase – my low-tech vehicle did not have this characteristic, and thus exhibited notable instability in flight. Another design characteristic I
decided to strive for is to have my wings not exhibit anhedral – that is that the positions where the top and bottom wings meet should create an angle up (not down) from horizontal, which is perpendicular to the fuselage. We actually decided to employ dihedral to this effect in the final design. This should help ensure that the aircraft does not execute an uncommanded roll in flight. It does this by creating a rolling moment when there is a sideslip – the wing towards which the aircraft is slipping will see a higher angle of attack, creating more lift on that side and rolling the aircraft back to level flight.

In the preliminary prototype, the rubber band was not a very good power source because it tended to jerk in motion rather than provide smooth, consistent power. This problem will be alleviated by the electric motor. Finally, the power supply – in this case, the rubber band – should not be aligned along the fuselage. By running flight tests and winding the rubber band in both directions, I concluded that the torque from the rubber band on the fuselage caused the vehicle to roll over in flight.
The final objective, since we did not manage to accomplish this in the semester, will be to introduce control surfaces on the body of the ornithopter – likely elevons and a rudder – and electronically controllable motor voltage. After attaching these to a radio receiver, the vehicle should theoretically be controllable with a remote control.

**Justification**

All creatures that fly naturally do so with flapping wings. The reason for this is that flapping wings are very efficient in small-scale and low-speed applications (2). However, our understanding of ornithopter flight has only recently been developed, and our knowledge is still somewhat incomplete. This project’s overarching goal is to contribute to that understanding, and allow for further experiments to take place on our ornithopter.

Professor Quinn’s biorobotics lab has been an excellent setting for this project. Previous projects have demonstrated the group’s expertise in robotics, and the Morphing Micro Air and Land Vehicle project – in conjunction with the Aerostructures lab – could be cited as an important benchmark for the group in aerodynamics research. This ornithopter project was a combination of the group’s strengths. I also gained insight from the robotics design and manufacturing expertise there, since I had very little experience in these areas.
Literature Review

As stated above, research on this topic has recently become more popular. As computational tools have become more capable, we have expanded our ability to shine light on the subject. However, there are some accepted theories regarding how these vehicles should operate and research into how they should be constructed.

The dominant force acting on the wing surfaces is pressure – if we treat the wing surface as a flat plate, we know that the surface hitting the incoming air will feel a higher pressure than the surface facing away. This analysis works well for static, steady-state scenarios, but when the wing’s angle of attack changes quickly we cannot assume steady-state. In fact, the dynamic-state of operation is a large contributor to ornithopter flight. The dynamic stall, captured in the “Wagner Effect”, describes a turbulent vortex propagating over a plate as the plate begins to move from a standstill. This vortex is responsible for much of the lift in ornithopters (1).

Another consideration is that the wing needs to be able to twist. If the wing does not rotate, then the upstroke will be identical to the down stroke and then net lift and thrust will be zero. Passively, this can be achieved by having a slightly stiff material supported only at the leading edge – the trailing edge will lag behind the leading edge in oscillation. According to Breitenstein 1, this is possible because aerodynamic and inertial loads on the wing will tend to decrease the angle of attack.
One interesting observation is that insects’ wings are rather flexible. This allows for bending and flexing during each flap cycle, which has the end effect of further decreasing the pressure above the wing and growing the leading-edge vortex (3). Of course, this results in more lift during the down stroke. The challenge here is to find a material for our wing spar that would be flexible enough to have such an effect, but rigid enough support aerodynamic loads.

**Materials and Methods**

I used the Aerostructures lab for the ability to mold and cut carbon fiber. We used woven carbon fiber for the fuselage, and unidirectional carbon fiber for the wing leading edges wing-supporting ballasts. In order to make the carbon fiber rigid it must be baked, so we needed to create molds to hold the components while they sat in the oven. I modeled this mold in SolidWorks, and tested that it would hold the proposed wing design. We then imported this design into Mastercam and generated tool paths. From this, we used a Hurco CNC machine to execute the machining. In order to prepare this mold for baking, I wrapped it in a sheet of Teflon so the carbon fiber would not stick to the mold.

We purchased the motor, battery, and gears from online sources. The key for these parts was to find materials that are light and cost-effective, since our initially planned budget was $300.
I will start my design analysis with the motor, which has a known “kv” rating. This rating has units “RPM per Volt”, and is essentially the ratio of the speed of the motor – without load – to input voltage. From there, I will be able to calculate what gear ratio is needed to create around 20 Hz flapping frequency. I was able to perform this reduction with only two gears. The gear attached to the motor has 9 teeth, and the driven gear has 60 teeth, for a gear reduction ratio of 6.67. Our motor will max around 12,000 RPM with no load, so if we approximate an average of one-third reduction from load we arrive at 8,000 RPM with load. 20 Hz is 1,200 RPM. The analysis here is light due to the low requirement for precision in this number – motor speed will be tunable using a speed controller. I then arranged the gears and motor on the carbon fiber fuselage to allow the wing spars to be driven by the final set of gears.

We needed to create a housing for the motor because it is an outrunner (the entire outer shell rotates) and because there are wires exposed in the back, but the motor still needs to sit securely in the fuselage. This need for close tolerances demanded a machining process, and we chose to manufacture it out of Delrin (polyoxymethylene). As before, this process involved designing in SolidWorks, generating tool paths in Mastercam, and machining with the Hurco.

The wing is a thin polyester-based plastic with woven thread support called Icarex, reinforced by carbon fiber strips for slight rigidity along the wing while remaining flexible along the chord. The leading edges were connected to wing joints, which we also designed and manufactured from Delrin. In future work, we will connect the wing leading edge to the driven gear in order
to actuate the flapping motion. We’ll control the voltage going into the motor using an electronic speed controller in order to tune the flapping speed and lift.

**Results**

The prototype, with balsa wood and tissue paper construction, was a success in construction. Its failure in flight served to teach us about the mechanics of ornithopters: again, the wings should flap in phase, the wings should exhibit dihedral, and the driving mechanism should point out the side rather than along the fuselage. Ultimately, I believe that this third design point would be less necessary if the wings would exhibit dihedral. However, we found that designing the motor to point out the front of the ornithopter would be infeasible, considering that the fuselage is very thin. Therefore, we still used a sideways-pointing orientation for the motor.

The final design that we achieved is influenced by these design characteristics, and contains the components illustrated in “Materials and Methods”. Even before completing construction, we realized the challenges of keeping tight tolerances on such a small scale. In using computer-aided-machining techniques with many of our parts, we did not factor in enough “room for error”. Thus we faced setbacks and unneeded repetition. Ultimately, we did not finish constructing the device. The two setbacks were the failure to adhere the Delrin to carbon fiber (see Appendix A), and the inability to design a linkage to connect the driven gear to the wing leading edge. This problem arises because a point on the wing, while flapping, has a
displacement component towards and away from the fuselage. This motion takes it out of the plane of the gear, which makes a direct linkage difficult.

As a whole, the design is quite satisfactory. While I did not meet the ultimate goal of fully assembling and testing the device, I believe that enough progress was made for another student in the lab to complete all of our goals (including the most ambitious – RC control) in the next year.
Future Work

The next step for this project is to resolve the design issue in connecting the driven gear to the wing leading edge. After this step is completed, a partially constructed device – with only wings, fuselage, motor, and gears – will be tested with off-board power to test lift characteristics, and the design may be modified again. After a suitable design is found, the ornithopter will be fully assembled with all electronics and the team will test the vehicle’s flight characteristics. At this point, the team will determine what types of control surfaces are necessary, and then will design and implement them. Finally, the vehicle will need to be tested again, and potential improvements will be evaluated.

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References


Appendix A: Design Elements

The end goal was to develop an ornithopter that would support its weight by flapping its wings in flight. It was also desired that the ornithopter would be scaled similarly to the Tobacco Horn Worm moth – this would limit our vehicle’s length and wingspan. Also, we were forced to find lightweight solutions to the problem of flight, because of the small size of our wing. To this end, we chose carbon fiber, plastics, and thin metal rods and tubes as our materials. We also purchased a small motor, and the lightest battery, speed controller, and gears we could find that matched our needs. We analyzed other existing ornithopter designs, including DelFly from Delft University. This gave us an idea of what wing shapes and sizes, fuselage shapes and sizes, and overall device layouts we should pursue.

Along the way, we analyzed the components we’d made, identified shortcomings and redesigned. The main issue where this was necessary was in the baking process. After machining the Delrin components and assembling them onto the carbon fiber in the molds and baking, we discovered that the smooth Delrin surface and the epoxy in the carbon fiber would not adhere. To combat this, we attempted to sand the Delrin and redesigned the wing joints such that the carbon fiber leading edges would span the entire wingspan – this would give the carbon fiber more surface area to stick to. We also discussed placing carbon fiber on both sides of the Delrin pieces in order to better hold them in place, knowing that carbon fiber should reliably adhere to itself. However, this was not implemented, and will be another design point to address in future work.
Throughout the entire project, I used SolidWorks to design and analyze the ornithopter. SolidWorks is a very common and powerful CAD program that is commercially available. I also used Mastercam to relay these designs to a Hurco CNC machine. Mastercam is also commercially available, and is software specifically to prepare tool paths for CNC machines. Hurco manufactures machines for labs and factories alike. These methods are much like those I would expect to encounter in the engineering and manufacturing workplace.