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Project # 3: Bio-Inspired Flight

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ABSTRACT

Bio-inspired flight uses the characteristics of bats, birds and insects to improve the function and structure of airfoils on airplanes and UAVs (unmanned aerial vehicles). By studying flying organisms and using the software technology of today, we can improve the design and role of aircraft to be more efficient than is currently possible. The goal of our research for this experience is to understand the forces that act on an aircraft, and ways we can look to nature to improve their design and function. In order to study this question, a basic knowledge of flight is required. The objectives for our research this summer included learning about principles of flight, and constructing and learning to operate a Zagi glider. The next step was the use of a smoke tunnel and different airfoil shapes to see the stream lines created, and then taking those observations to create a new type of airfoil for micro air vehicles. We chose to study corrugated airfoils similar in profile to the wings of a dragonfly by creating the corrugated shape and testing its lift and drag in a wind tunnel. By recording observations and analyzing the data about its flight, AeroMorph technology can be used to develop and implement new bio-inspired airfoil designs. Based on current research on corrugated airfoils at low Reynolds numbers, we tested smooth and corrugated airfoils in a wind tunnel and analyzed the data on their lift and drag. Our data suggests the same conclusion as the literature we reviewed, which is that although the corrugated airfoil would seem to have unfavorable aerodynamics, it in fact performs as well as, or better, than the tradition smooth airfoils which perform well at higher Reynolds numbers. At the end of the project, we concluded that with continued research and a clearer understanding of flight in nature, engineers will be able to produce wings of micro air vehicles that mimic those of insects like dragonflies, in order to increase function and efficiency of this type of aircraft.

Key Words: Airfoil, bio-inspired, corrugated, Reynolds number, lift, drag, micro air vehicle

TABLE OF CONTENTS

Item	Page No.
Cover Page	1
Abstract	2
Table of Contents	3
1. Introduction	4
2. Literature Review	4
3. Goals and Objectives	4
4. Background Information	5
5. Research Methods	8
6. Research Data Analysis	10
7. Conclusions	16
9. Recommendations for Further Study	16
10. Acknowledgements	16
11. References	17

1. INTRODUCTION

When it comes to engineering a micro air vehicle (MAV), which is designed to function near the ground, the research suggests that the traditional rules of airfoil design do not hold true. Traditional airfoils are designed to function in the conditions of the atmosphere several thousand feet above ground. The air density and viscosity are very different, as well as the speed at which large aircraft need to fly to maintain lift. With this in mind, designers of MAVs must look to insect and bird flight to understand the requirements of low Reynolds number flight. This refers to flight conditions near the ground, which include lower speeds, smaller airfoils, and air that is much more dense and viscous.

Although the forces that act on an aircraft and those that act on flying insects, bats, and birds are the same, the interactions of those forces with the flight conditions on the small scale are not. Engineers have analyzed the wing structures of flying creatures and have realized that they are very different than those of engineered human flight. In the case of the dragonfly, several million years of evolution have not changed the wing structures, indicating that the design must be extremely efficient since these insects are masters of flight. In order to create MAVs which can serve in such capacities as reconnaissance, wildfire fighting, and security functions, humans must master the domain of small scale flight. We will only be able to accomplish this if we learn and replicate the forms and functions that have served creatures like dragonflies well for millennia.

2. GOALS OF THE STUDY

This project studies the methods and characteristics of the flight of insects to improve the design and function of aircraft by investigating trends in airfoil design as they move towards bio-inspired micro-UAVs. The goal of this study was to study the methods and characteristics of the flight of insects to improve the design and function of aircraft by investigating trends in airfoil design as they move towards bio-inspired micro-UAVs. The objectives were to understand the principles of flight, to use them to control the Zagi glider, design airfoils and carve them from foam, and test them in the wind tunnel.

3. LITERATURE REVIEW

In studying the wing structure of dragonflies it was found that the cross section is corrugated. Before 2008 there had been no quantitative flow measurements made to determine the reason that corrugated airfoils could have comparable, or even superior, aerodynamic performance at low Reynolds number flight (Hu and Tamai, 2008). When PIV (particle image velocimetry) was conducted on models of dragonfly wings at various angles of attack, and then compared to that of a conventional streamlined airfoil and a flat plate, it was

found that the corrugated airfoil had no apparent boundary layer separation. This was an unexpected finding since the traditional understanding of airfoils required that they be smooth. When tested for drag and lift, these airfoils performed at least as well, if not better than, smooth technical airfoils (Kesel, 2000).

Kesel (2000) hypothesized that the corrugated structure served as an intermediary form of cambered (curved), flat and asymmetric airfoils.

Figure 1: Dragonfly Wing and its profile

Lift and drag analysis in a wind tunnel at low Reynolds numbers (>300,000) have shown that although technical airfoils, like flat plates and curved plates, get more lift under similar conditions, the corrugated airfoils are more efficient and have significantly less drag (Kwok and Mittal, 2005). Kesel (2000) and Hu and Tamai (2008) explain that the corrugated surface causes reverse flows or vortices in the channels of the structure and that these act as cushions to provide a smooth streamline over the channels. Dragonfly wings actually suppress large scale flow separation and stall with protrusions on the corners of their wings that act to generate unsteady vortices that promote the transition of the boundary layer from laminar to turbulent very quickly (Tamai, Wang, Rajagoplanan, Hu and He, 2007). Kesel's tests compared the dragonfly profile to airfoils which had the same profile with the channels filled in. The filled profiles had a significant reduction in lift (Kesel, 2000). Apparently nature perfected a low Reynolds number airfoil several million years ago and its superiority has provided these insects with a distinct evolutionary advantage that has remained unchanged for millennia.

4. BACKGROUND INFORMATION

The project started with learning the basic physics principles involved in flight, and demonstrations of the wind tunnels used to collect airfoil test data. There are four forces that affect the motion of an aircraft, animal or insect in flight. These are weight, thrust, lift and drag, and act on the aircraft at either the center of gravity or the center of pressure as shown in **Figure 2**.

Figure 2: Forces acting on an aircraft

The project team also studied Bernoulli's principle to understand how lift is generated. Here is Bernoulli's Equation in its integral form:

$$P_1 + \frac{1}{2}\rho V_i^2 = P_2 + \frac{1}{2}\rho V_2^2 = P_0 \qquad (1)$$

where P = force in Newtons/square meter (N/m^2), ρ = density in kg/m^2 and V = velocity in m/s. Essentially, the Bernoulli principle is due to the pressure difference above and below the wing of an aircraft. This pressure difference is caused by the high speed the air has as it moves over the wing. In order for a plane, bird, bat, or insect to get off the ground, lift must be generated. In an aircraft this is accomplished by the movement of air over the wing, which lowers the pressure above it, while the pressure below stays as it was. This pressure difference pushes the plane up, hence the term lift. The lift acts on the plane at its center of pressure and must be large enough to overcome the weight of the plane, which acts on the plane's center of gravity. These two areas are usually very close to one another on the body of the plane. The thrust is applied by the engine(s) and is directed toward the back of the aircraft to provide the forward force. Drag, or a slowing of the plane as it tries to push itself through the air, is in the exact opposite direction of thrust, and is due to Newton's Third Law of Motion. If the thrust is inadequate, the plane will not move forward fast enough to lower the pressure over the wing, and the plane will not leave the ground. The altitude is affected by the amount of lift, which must be larger than the weight of the aircraft.

There are several factors involved in the amount of lift an airfoil gives to an aircraft. The camber or curvature of the wing, the angle of attack, and the velocity of the air past the wing combine to determine the efficiency of flight.

Because of the interactions of the four forces, there are also characteristic motions which must be controlled to prevent stall (nose up) or dive (nose down). These are yaw, pitch, and roll. The design of an airfoil, its camber, and the angle of attack, allow these factors to be controlled. One tool that aerospace engineers use to define these dynamics is the Reynolds number, which comes from an equation describing the relationship of the density and viscosity of the air, the speed of the air over the wing, and the length of the airfoil (wing) itself. The equation is

$$\mathrm{Re} = \frac{\rho V \chi}{\mu} \tag{2}$$

where ρ= density in kg/m^2, V = velocity in m/s, μ = fluid viscosity in kg/m.s, and χ = chord length in meters. Another way to describe the Reynolds number is the dimensionless ratio between inertial forces and viscous forces. Chord length refers to the distance from the leading edge of the airfoil to the trailing edge. The velocity of aircraft, since they fly near the speed of sound, can be described by a Mach number, which is the speed of the airplane divided by the speed of sound.

When the plane, or creature for that matter, is in flight, the forces on it must be balanced. A pilot trims (balances) a plane by devices on the aircraft that control roll, pitch and yaw. Roll is the motion that raises one wing and lowers the other. Pitch changes the level of the nose compared to the tail, and yaw moves the nose and tail left or right in relation to each other. Birds and bats bend their wings into various shapes to control these motions, and planes are equipped with rudders, flaps and ailerons.

In addition to controlling flight by controlling the speed and orientation of the center of gravity of the aircraft, the wings also control how much lift is generated by the angle at which they are mounted on the aircraft, called the angle of attack. There are several equations which allow the calculation of the lift coefficient at various angles of attack. One common form of the equation is

$$C_L = 2\pi\alpha + C_{LO} \tag{3}$$

where C_L = lift coefficient, α = angle of attack in degrees, and C_{LO} = lift coefficient at 0 angle of attack. This is also known as the thin airfoil equation. In general, an aircraft should have a high lift coefficient, and a low drag coefficient to fly with high efficiency. The higher the angle of attack, the more lift is generated to a point, after which stall occurs and the lift drops to zero. **Figure 3** shows a graph of lift coefficient versus angle of attack. It shows that as the angle of attack increases, the lift increases in direct proportion. But at about 16°, the lift drops dramatically. This is known as stall, and is not a desired situation for an aircraft.

Figure 3: Graph lift coefficient versus angle of attack showing stall5. RESEARCH METHODS

For this study several approaches to assemble information about the characteristics of flight in a bio-inspired airfoil were used. The research took place in two-week segments. The first two weeks were centered on learning the principles of flight. The next two weeks involved a literature review of the trends in bio-inspired airfoil design and assembling the Zagi glider (see **Figure 4**). At the end of this segment we flew the gliders in Nippert Stadium in order to put the principles of flight into practice in controlling the flaps, or elevons, in order to control the path of the Zagi. In the final phase, we used the dragonfly wing profile as a template to carve two bio-inspired airfoils for testing in the wind tunnels.

Figure 4: Zagi glider and its radio remote controller

There were two types of wind tunnels used in this research. The smoke tunnel allows the streamlines to be clearly seen, as well as vortices and low pressure areas around the object.

The teachers observed several airfoil shapes and some toy cars, noting the type of flow generated and the vortices created by each and some results are presented in **Figures 5 and 6**.

Figure 5: Technical airfoil showing smooth streamlines - this airfoil shows less separation behind it

Figure 6: Dragonfly airfoil showing similar streamlines.
Separation is more pronounced.

The teachers then went on to carve an airfoil from dense foam to test in the large wind tunnel (see **Figure 7**), and one from balsa wood for use in the smoke tunnel. Although the smoke tunnel does not record data, it is useful for visualizing where flow separation occurs and is a useful tool when combined with lift and drag data from the large tunnel. Although the data here is not from the true profile of the dragonfly wing due to equipment limitations, the profile was made to be similar in each characteristic to the technical airfoil (i.e., chord length, surface covering, etc.) while carving the corrugations to be as similar to the dragonfly profile as possible, thus allowing the most direct comparison of their flight characteristics. This wind tunnel used allows measurements to be made of the lift and drag on an airfoil at airspeeds between 5 m/s and 50 m/s. Two foam airfoils were tested, as shown in **Figures 8 and 9**. The LRN1015 (low Reynolds number with chord thickness of 15% the chord length) and the dragonfly profile were compared using several graphs. The data was collected in the form of a text file and Excel was used to generate the graphs from the data. The teachers graphed the following: lift versus drag at α (angles of attack) of -18, -12, -6, 0, 6, 12, and 18 degrees, lift versus the wind velocities of 5 m/s, 10, 15, 20, 25 and 30 m/s, and efficiency of the airfoils (lift/drag) versus the angle of attack at the same velocities. Using XFOIL, a simulation software program used to show data under perfect conditions, the teachers compared the highest and lowest speeds (5 m/s and 30 m/s) to their actual data. XFOIL calculates the lift coefficient given the length, wing area, air density and air speed. The ideal and actual graph lines were compared to see the effects of experimental uncertainty in their real data from the wind tunnel. The graphs on next section show the data collected and analyzed.

Figure 7: Wind tunnel for lift and drag measurements

Figure 8:Dragonfly-inspired airfoil in the wind tunnel at α = 0 degree

Figure 9 :LRN1015 smooth airfoil at α = 0 degree

6. RESEARCH DATA ANALYSIS

Comparisons of the data for the LRN1015 airfoil and the dragonfly airfoil revealed several very interesting things about corrugated airfoils, which were in keeping with the findings in the literature reviewed for this experiment. The results obtained for drag versus lift are shown in **Figures 10 and 11** for LRN1015 and dragonfly, respectively. The graph in **Figure 10** shows that, as expected, drag increases with increased lift. The increase is not linear for the increased drag at various angles of attack. As the angle of attack increases in either the positive or negative direction, the drag increases exponentially. The highest drag values are at -18 and 18 degrees angle of attack. Also apparent from the graph is the fact that negative lift (from negative angle of attack) does not result in negative drag. Negative drag is a physical impossibility.

As can be seen in **Figure 11**, in the corrugated airfoil, the drag is noticeably more consistent. The overlapping lines for the various angles of attack show that changing alpha barely changes the amount of drag on the airfoil. The smallest drag is found at -6, 0, and 6 degrees. This is in line with the demands of the various types of flight that dragonflies must execute daily to

Figure 10: Drag Versus Lift for LRN1015

Figure 11: Drag Versus Lift for Dragonfly Model

survive. These insects fly at very low Reynolds numbers of around 7000 (Kesel, 2000). Below are the computations of the Reynolds numbers for the wind tunnel tests on both airfoils. The shape of the airfoil does not play a part in this calculation, and so the Re values are exactly the same for both airfoils at the same speed and angle of attack.

LRN1015	Density(Kg/m^3)	1.19
	Length (m)	0.108
	Viscosity (Kg/m*s)	0.0000178
Velocity(m/s)	Reynolds Number	
5	36101.1236	
10	72202.24719	
15	108303.3708	
20	144404.4944	
25	180505.618	
30	216606.7416	

Dragonfly	Density(Kg/m^3)	1.19
	Length (m)	0.108
	Viscosity (Kg/m*s)	0.0000178
Velocity(m/s)	Reynolds Number	
5	36101.1236	
10	72202.24719	
15	108303.3708	
20	144404.4944	
25	180505.618	
30	216606.7416	

The results obtained for lift/drag versus angle of attack are presented in **Figures 12 and 13** for LRN1015 and dragonfly, respectively. The data trend of **Figure 12** shows that the efficiency(lift/drag) changes with the angle of attack, as well as with the speed . This particular airfoil functions most efficiently at 15 m/s, which corresponds to Re = 108,000. The variations in efficiency at various velocities highlights the fact that technical airfoils are designed for one type of flight, and do not have the flexibility of a corrugated airfoil, designed for lower Reynolds number flight. It is interesting to compare the consistency of the efficiencies of the dragonfly model at what are widely varying speeds for an insect. The dragonfly profile (see **Figure 13**) reaches peak efficiencies over a wider range of speeds and angles of attack. It is perhaps not accidental that a corrugated airfoil would give a dragonfly the most efficient flight at about half of its top gliding speed of 10 m/s.

The results obtained for lift versus angle of attack are presented in **Figures 14 and 15** for LRN1015 and dragonfly, respectively. In comparing the lift to the angle of attack it is striking that again the LRN1015 profile stalls at smaller angles of attack than the corrugated profile, which only shows the beginning of stall at the 30 m/s velocity. Although the LRN1015 generates more lift, especially in the -5 degree range where the lift on the dragonfly airfoil is nearly zero, the maximum lift coefficient for the corrugated airfoil is an impressive 18 degrees. The dragonfly airfoil has a more linear relationship between lift and angle of attack than does the LRN1015.

Figure 12: Lift/Drag Versus Angle of Attack for LRN1015

Figure 13: Lift/Drag Versus Angle of Attack for Dragonfly (Corugated) Model

Figure 14: Lift Versus Angle of Attack for LRN1015

Figure 15: Lift Versus Angle of Attack for Dragonfly (Corrugated) Model

The results obtained for the lift/drag coefficient from the wind tunnel and the XFOIL analysis is presented in **Figures 16 and 17** for a particular wind velocity. The data above shows that the wind tunnel had some experimental uncertainties. Compared with the XFOIL analysis, our wind tunnel did have the same general trend. The same is true for the 30 m/s data, and it appears that in the wind tunnel the uncertainties are a bit less pronounced at higher speeds.

Figure 16: Lift Coefficient Versus Angle of Attack for 5 m/s

Figure 17: Drag Coefficient Versus Angle of Attack for 5 m/s

The XFOIL analysis shows the discrepancy between the data generated by the wind tunnel and the ideal data. Some sources for this discrepancy are the construction irregularities inherent in carving the airfoils from foam and covering them with paper. The dragonfly profile was not cut with a template, as one was not available to us due to time and equipment constraints. The paper itself is actually fairly rough under the conditions in the tunnel, and invisible turbulence caused by the texture of the paper and the vibration of the airfoils in the tunnel no doubt contributed to the imperfect nature of our data. In addition to the turbulence, the vibration also changed the angle of attack slightly, but constantly, during the testing. Finally, the wires used to hold the airfoil in place in the tunnel also contributed to the variations in data patterns suggested by XFOIL.

7. CONCLUSIONS

After careful comparisons of the various aspects of wind tunnel data taken on the technical (LRN1015) airfoil and the corrugated (dragonfly) airfoil, it is apparent that the design of MAVs should be closely aligned with the nature-inspired airfoil properties for greatest efficiency and maneuverability. The atmospheric conditions, such as air viscosity and density, in which MAVs will be flown are similar, if not exactly the same as that of insects with corrugated airfoils. Technical airfoils are designed for high speed, low density and low viscosity flight, and they function very well for this purpose. However, MAVs utility will be employed very differently, and so require new ideas for their designs. Our data, which is supported by that in the literature, suggests the inspiration for those ideas should come from nature's designs. The superior properties of corrugated airfoils for low Reynolds number flight cannot be doubted.

8. RECOMMENDATIONS FOR FURTHER STUDY

In doing the literature review for this study, we noticed the relative dearth of work on corrugated airfoils. This field is so wide open in its possibilities. Are there other insects whose airfoils have different and superior characteristics? Are there an optimal number of channels on a corrugated wing? Is there an optimal spacing of channels based on size and speed of the intended MAV? There are more questions to ask than there are researchers to study them, and it will be interesting to see where the world of engineering research takes these questions in the future.

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