THEORY OF WINGS

AND

WIND TUNNEL TESTING OF A NACA 2415 AIRFOIL

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Technical Communication for Engineers
The University of British Columbia
July 23, 2001
ABSTRACT

“Theory of Wings and Wind Tunnel Testing of a NACA 2415 Airfoil”
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The purpose of this report is to familiarize the reader with the basic aerodynamic theory of wings and to provide an introduction to wind tunnel testing. This introduction is followed by the results from the wind tunnel testing of a NACA 2415 wing and the analysis of this data. The analysis is to be used for the construction of a radio controlled Vertical Take Off and Land vehicle (VTOL) model, with the potential for use on a full-scale commercial vehicle in the near future. The following conclusions have been drawn from analysis of the data.

Lift increases as the angle of attack increases between -5 and +17 degrees and at +17 degrees maximum lift is generated. If the angle of attack is increased any further, drag becomes the dominant factor and the wing enters the stall mode. When the lift vs. drag coefficients are compared with the theoretical data from the National Airfoil Database for the wing, it is evident that the existing test section generates significantly more drag than expected. This is primarily caused by the imperfections in the construction of the wing section and inaccuracies in the experiment. Consequently, the author makes a few recommendations that would improve the quality of the experiment and would reduce these errors.
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**GLOSSARY**

**Force Balance:**
Besides lift, drag and pitching moment, the airplane is subject to rolling moment, yawing moment and side force. The wind tunnel force balance is machine that separates these forces and moments and accurately presents the small differences in large forces.

**Drag:**
Drag is the aerodynamic force that opposes an aircraft's motion through the air. It is a mechanical force that is by the interaction and contact of a solid body with a fluid (liquid or gas). It is not generated by a force field, in the sense of a gravitational field or an electromagnetic field, where one object can affect another object without being in physical contact. For drag to be generated, the solid body must be in contact with the fluid. If there is no fluid, there is no drag. Drag is generated by the difference in velocity between the solid object and the fluid. There must be motion between the object and the fluid. If there is no motion, there is no drag. It makes no difference whether the object moves through a static fluid or whether the fluid moves past a static solid object. Drag acts in a direction that opposes the motion. (Lift acts perpendicular to the motion.)

**Reynolds Number:**
The primary parameter correlating the viscous behaviour of all Newtonian fluids is the dimensionless Reynolds Number:

\[ \text{Re} = \frac{\rho V L}{\mu} \]

Where \( V \) is the stream velocity, \( L \) is the length of the body, \( \rho \) is the fluid density and \( \mu \) is the fluid viscosity.

**Stall:**
As an object moves through the air, air molecules stick to the surface. This creates a layer of air near the surface (called a boundary layer) which, in effect, changes the shape of the object. The flow turning reacts to the boundary layer just as it would to the physical surface of the object. To make things more confusing, the boundary layer may lift off or "separate" from the body and create an effective shape much different from the physical shape. This occurs at higher angles of attack; determining the drag when the flow is separated is very difficult. The separation of the boundary layer explains why aircraft wings will abruptly lose lift at high inclination to the flow. This condition is called a stall.
1.0 INTRODUCTION

The purpose of this report is to present an Introduction to structure and theory of wings. Also, it includes some background information on wind tunnels and wind tunnel testing. Lastly, this report describes the procedure for testing the NACA 2415 airfoil and presents a number of graphs and tables evaluating the data obtained through these tests. The objective is to find the angle of attack at which the lift is maximized in order to get the best performance of this wing when in flight.

The wind tunnel testing of NACA 2415 airfoil is the first step towards building and testing a Remote Controlled Vertical Take off and Land Aircraft (r/c VTOL). This small r/c aircraft has great potential for commercial use, since it does not need much space for take off and is much faster than a helicopter; as a result, it could be used for different operations in various locations including mountains and forests. My previous research has shown that NACA 2415 has superior lift versus drag characteristics suitable for the r/c VTOL, and this report has tried to demonstrate these characteristics by presenting the results from the wind tunnel testing of this airfoil.

This report is based on the author’s research on basic aerodynamics of wings and fundamentals of wind tunnel testing. In addition, it will present the results from testing the NACA 2415. These test have been conducted using one of the small wind tunnels at the UBC Areolab located in the Rusty Hut. This data is then presented through tables and graphs using Microsoft Excel.
2.0 STRUCTURE AND THEORY OF WINGS

Wing is an aerodynamic structure that generates lift when comes into contact with moving air molecules i.e. wind. The lift is generated due to the wing’s unique shape. It is curved on the upper surface and is almost flat on the bottom surface. This unusual form causes the air to go faster over the top than the bottom. This difference in speed results in a difference in pressure between the top and the bottom of the wing which exerts an upward net force on the wing. This upward force is called lift.

The amount of lift obtained from the wing depends on the shape of its airfoil and its angle of incidence. There is usually a relationship between the angle at which the wing is permanently inclined to the airplane’s longitudinal axis and the amount of lift generated. At small angles, as the angle of attack is increased the lift increases; however at a certain point the drag* on the wing dominates the lift and the aircraft goes into stall*.

Each wing section has a certain airfoil that could be categorized as either laminar or conventional the difference between these two types of airfoils is discussed later in the section.

2.1 THEORY OF LIFT

![Figure 1. Four Forces Acting on the Plane](http://www.allstar.fiu.edu/aerojava/flight11.htm)

An airplane in flight is the center of a continuous tug of war between four forces: lift, gravity force or weight, thrust, and drag. Lift and Drag are considered aerodynamic forces because they exist due to the movement of the aircraft through the air. The weight

*This and all subsequent terms marked with an asterisk are defined in the Glossary, pp. v.
pulls down on the plane opposing the lift created by air flowing over the wing. Thrust is generated by the propeller and opposes drag caused by air resistance to the frontal area of the airplane. During take off, thrust must overcome drag and lift must overcome the weight before the airplane can become airborne. In level flight at constant speed, thrust exactly equals drag and lift exactly equals the weight or gravity force. For landings thrust must be reduced below the level of drag and lift below the level of the gravity force or weight.1

Figure 2. Air Flow through the Wing
Source: http://www.allstar.fiu.edu/aerojava/flight11.htm

Lift is produced by a lower pressure created on the upper surface of an airplane's wing compared to the pressure on the wing's lower surface, causing the wing to be "lifted" upward. The special shape of the airplane wing (airfoil) is designed so that air flowing over it will have to travel a greater distance faster, resulting in a lower pressure area (see illustration) thus lifting the wing upward.2
2.2 THE AIRFOIL

Conventional and Laminar flow airfoils are in common use in airplane design. Laminar flow airfoils were originally developed for the purpose of making an airplane fly faster. The laminar flow wing is usually thinner than the conventional airfoil, the leading edge is more pointed and its upper and lower surfaces are nearly symmetrical. The major and most important difference between the two types of airfoil is that the thickest part of a laminar wing (maximum camber) occurs at 50% chord while in the conventional design the thickest part is at 25% chord as show in fig 7.3
The effect achieved by this type of design of a wing is to maintain the laminar flow of air throughout a greater percentage of the chord of the wing and to control the transition point. Drag is therefore considerably reduced since the laminar airfoil takes less energy to slide through the air. The pressure distribution on the laminar flow wing is much more even since the camber of the wing from the leading edge to the point of maximum camber is more gradual than on the conventional airfoil. This is illustrated in figure 7. However, at the point of stall, the transition point moves more rapidly forward. Different types of conventional airfoils are shown in figure 8.⁴

![Figure 8. Different Types of Airfoils](http://www.allstar.fiu.edu/aerojava/flight11.htm)
2.3 ANGLE OF INCIDENCE

The angle of incidence is the angle at which the wing is permanently inclined to the airplane’s longitudinal axis. Choosing the right angle of incidence can improve flight visibility, enhance take-off and landing characteristics and reduce drag in level flight.

![Figure 9. Angle of Incidence of the Wing](http://www.allstar.fiu.edu/aerojava/flight11.htm)

The angle of incidence that is usually chosen is the angle of attack at which the lift-drag ratio is optimum as shown in fig 9. In most modern airplanes, there is a small positive angle of incidence so that the wing has a slight angle of attack when the airplane is in level cruising flight.5

![Figure 10. Relationship Between Lift and the Angle of Attack](http://www.lerc.nasa.gov/WWW/K-12/airplane/airplane.html)

For small angles, lift is related to angle.  
**Greater Angle = Greater Lift**

For larger angles, the lift relation is complex.  
**Included in Lift Coefficient**
3.0 WIND TUNNEL TESTING OF THE AIRFOIL

Wind tunnel testing is a crucial step in the design of an aircraft. It can give quite accurate information on the performance of an aircraft or a section of an aircraft by taking data on a scale model. This can save enormous amounts of money by testing models instead of prototypes. It is also much safer to test in a wind tunnel than out in the open. The following section covers the theory of the wind tunnels and procedures for testing the NACA 2415 airfoil.

3.1 THEORY OF WIND TUNNELS

All wind tunnels can be divided into one of two types: open circuit (also called “straight through”) or closed circuit (also called “return flow”). Open circuit wind tunnels pull the air from the environment into the tunnel and release the air back into the environment, whereas the closed circuit continually circulates the same air throughout the tunnel. The wind tunnel we used is a single return flow wind tunnel, shown in Figure 11.

Figure 11. The wind tunnel we used to test our airfoil.

Closed circuit wind tunnels are advantageous over open circuit wind tunnels for the following reasons: the quality of the flow can be easily controlled with screens and corner turning vanes; less energy is required to create an airflow of a given size and
velocity; the wind tunnel runs more quietly. The disadvantages are the initial expense of building and need to change the air if it is significantly heated or polluted with smoke from smoke testing or engines\textsuperscript{7}. Fortunately, neither of the disadvantages affected us.

### 3.2 PROCEDURES OF TESTING THE NACA 2415 AIRFOIL

My goal was to find the coefficients of lift and drag, $C_L$ and $C_D$, respectively. These coefficients are defined as follows:

\begin{align*}
C_L &= \frac{2L}{(dv^2A)} \quad (1) \\
C_D &= \frac{2D}{(dv^2A)} \quad (2)
\end{align*}

Where $L$ is the lift force in N, $D$ is the drag force also in N, $d$ is the density of the air in kg/m\(^3\), $v$ is the velocity of the air in m/s, and $A$ is the horizontal area of the wing in m\(^2\).

The first step was to find the velocity of the airflow. Quite simply using a manometer to compare the pressure at two different places in the wind tunnel having two different cross-sectional areas did this. The velocity could then be calculated using the equation:

\[ V = 4.3*(\Delta h)^{0.5} \quad (3) \]

Where $\Delta h$ is the difference in height between the two levels of the distilled water in the manometer measured in mm. For our testing, $\Delta h$ was 17.4mm, therefore the velocity was 19.7 m/s. The area of the wing was taken as the chord length (26.2cm) multiplied by the length of the section (55.6cm), giving a total area of 0.1457m\(^2\). The density of air is 1.20kg/m\(^3\) at room temperature. The final parameters required calculating the two coefficients are the

\[ \text{Fig 12. Force balance interface.} \]
corresponding forces. The force balance interface (Figure 12) displays values of the voltages created by the force balance, which are linearly proportional to forces. Because my airfoil was oriented sideways, the lift force was actually a “side” force. The force can be calculated by multiplying the voltage by the slope of the calibration curve, 31.112 N/mV. This curve could be found in the calibration manual. Similarly, the Drag can be calculated by multiplying the voltage by 37.3798 N/mV. At zero degrees, the voltage for the lift force was 0.102 mV and the voltage for the drag force was 0.015 mV. By using (1) and (2) we calculated $C_L$ to be 0.0702 s²/kg and $C_D$ to be 0.0124 s²/kg. The rest of the data are displayed below in Table 1 and shown graphically in Figure 13 and Figure 14.

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Table 1. Data obtained from wind tunnel testing for V=20 m/s.
Figure 13. Coefficients of Lift and Drag versus Angle of Attack

Figure 14. Lift Versus Coefficient of Drag
As you can see from Figure 13, the results show a relationship between the coefficient of lift and angle of attack. Looking at the graph in fig 13, it can be concluded that the optimum angle of attack is between 15-17 degrees. The reason is that at this range the ratio between the coefficient of lift and the angle of attack is at its maximum. As a result, it is reasonable to assume that in order to obtain maximum lift from NACA 2415 airfoil, the wing needs to be positioned at 15-17 degrees with respect to the flight path.

Furthermore, we can observe that after the peak occurs at around 17 degrees the coefficient of drag starts increasing at an exponential rate, which is shown in Figure 14. This exponential rate of increase demonstrates that if the angle of attack is increased any further the drag will dominate lift and stall will occur.

There is also a relationship between the coefficients of lift and coefficient of drag shown in Figure 14. Although it is not so well defined. There was significantly more drag than in testing done at UIUC (figure15) on the same airfoil with a Reynolds number* of 200600 compared to our 341466. This extra drag is assumed to be primarily caused by imperfections in the airfoil construction and the inaccuracies in the experiment.

![Graph showing relationship between CL and CD](image)

**Figure 15.** UIUC Theoretical Idealized Data for the NACA 2415
5.0 CONCLUSION

In an aircraft, lift is caused by an upward force that is resulted from the difference in pressure between the top and the bottom surface of the wings. This difference in pressure is due to the special shape of the airfoil, and the amount of this lift is dependent upon the angle at which the wing is inclined.

To find the maximum performance of the wing, it should be tested in a wind tunnel at different angles of attack. From testing the NACA 2415 it is determined that the optimum angle of attack is between 15-17 degrees. Unfortunately, excessive drag is generated by the inaccuracies in the construction of the wing and the errors in the experiment.

In order to decrease this drag, a softer type of fiberglass can be used to cover the wing to decrease the friction between air and the wing surface. Also, there are a few concavities on the surface of the wing that resulted from the dissolution of foam by the resin. To avoid these concavities a few layers of plastic paint could be applied to the surface of the wing before covering it with the resinated fiberglass.

As it can be observed from the left graph in Figure 15, The NACA 2415 airfoil has superior lift versus drag characteristics suitable for the Radio Controlled Vertical Take off and Land Aircraft. The results from testing the existing wing section are close to the theoretical results from the National Airfoil Database (Figure 15); however, as mentioned before, excess drag is generated. Therefore, the next step would be to improve the errors in the construction of the test section and the set up of the experiment. Moreover a few more tests need to be done to match the experimental data with the theoretical data.
REFERENCES


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