

Aerodynamic forces acting on an airfoil

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Abstract

Wind tunnel testing was conducted on NACA 3314, NACA 8321, NACA 1209, NACA 6217, NACA 0014, and NACA 5417 airfoils. The lift and drag forces acting on each of the airfoils were successfully measured with an airflow velocity of 14.4 m/s, and an angle of attack for the airfoils of 20° relative to airflow. The experimentation allowed a comparison of flight characteristics between the airfoils, in which each generated an expected range of lift and drag forces. The exception was the NACA 6217 airfoil that produced more lift than expected. A correct theory of lift was identified and visually confirmed as well.

1 Introduction

An airfoil is defined as the cross section of a body that is placed in an airstream in order to produce a useful aerodynamic force in the most efficient manner possible [1]. The cross sections of wings, propeller blades, windmill blades, compressor and turbine blades in a jet engine, and hydrofoils are example airfoils. This experiment will focus on airfoils as the aircraft wings. The basic geometry of an airfoil is shown in Figure 1. The most important features of airfoil geometry are the chord, camber, and thickness. The straight line connecting the leading and trailing edges is the chord line, the distance measured between the trailing and leading edge along the chord line is the chord of an airfoil. The line

of points that are halfway between the upper and lower surfaces is the mean camber line as measured perpendicularly from the chord line. The thickness of an airfoil is the distance from the upper and lower surfaces as measured perpendicularly to the chord line, and varies in distance along the chord line. Camber is the maximum distance that occurs between the mean camber line and the chord line. Maximum camber and thickness, as well as where they occur along the chord line, are important design components for airfoils, and are used in the classification of airfoils.

Lift is defined as the component of aerodynamic force perpendicular to the relative airflow. There are multiple incorrect theories concerning the generation lift. The theory

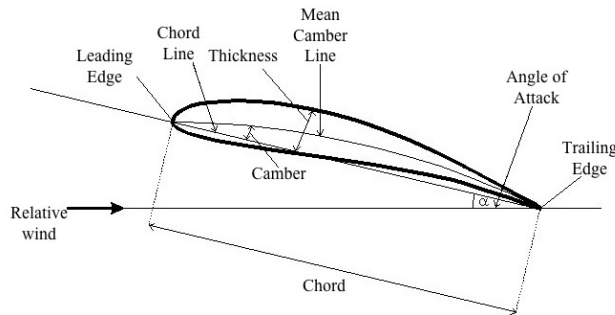


Figure 1: Diagram of airfoil's geometry. [2]

most commonly found in text books and pilot training manuals utilizes Bernoulli's principle which states that for a liquid or gas, areas with high relative velocity create lower pressure systems, and areas with low relative velocity create high pressure systems. The theory states that airfoils are shaped so that the upper surface is longer than the lower surface; therefore, when air molecules are separated by the leading edge of the airfoil, they have a greater distance to travel as they cross the upper surface than along the lower surface. Thus, in order for the air molecules to meet at the trailing edge at the same time, the molecules traveling along the upper surface must be traveling faster than the air molecules along the bottom surface. Since the airflow on the upper surface is faster, Bernoulli's principle states that a lower pressure system is created. The difference between the low pressure above the airfoil and the higher pressure below causes lift to occur. However, there are no principles of fluid dynamics stating that two free moving air particles must meet at a single point beyond an

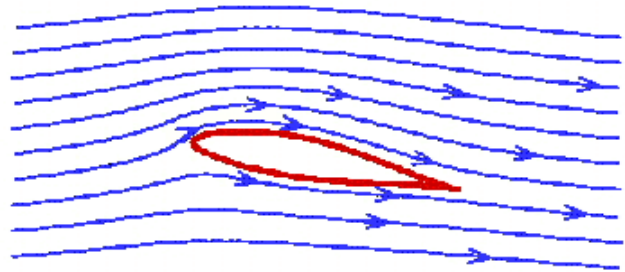


Figure 2: Airflow about an airfoil according to the flow turning theory. [2]

obstacle once separated by the obstacle.

The correct theory of lift generation is known as the flow turning theory. It states that the airfoil bends the direction of the airflow around it as the airflow passes over the upper surface, and creates a vertical velocity of airflow past the trailing edge. The effect of the airflow bending is due to the viscosity of a fluid and the Coanda effect [3]. As the airfoil bends the airflow near the upper surface, it pulls on the air above it and causes an acceleration of that air down to the airfoil. The pulling of the air causes a low pressure system to form over the airfoil creating a net force that is lift. Figure 2 demonstrates airflow about an airfoil generating lift by the flow turning theory.

The other aerodynamic force that affects an airfoil in a wind tunnel is perpendicular to the lifting force, called drag. The airfoil experiences a drag force that opposes the relative motion of the airfoil and has direction parallel to the airflow [4]. Skin friction drag is the friction that occurs between the air molecules and the surface of the airfoil. Form drag is dependent on the overall shape of the air-

foil, and pertains to the pressure distribution about the airfoil's surface. As with the lifting force, the airfoil changes the local momentum of the air around it, affecting the velocity and pressure. The resulting pressure distribution produces a force that acts on the airfoil.

2 Theory

The equations for calculating lift and drag are very similar. The lift that an airfoil generates depends on the density of the air, the velocity of the airflow, the viscosity and compressibility of the air, the surface area of the airfoil, the shape of the airfoil, and the angle of the airfoil's angle of attack. However, dependence on the airfoil's shape, the angle of attack, air viscosity and compressibility are very complex. Thus, they are characterized by a single variable in the lift equation, called the lift coefficient. Due to the complexities of the lift coefficient, it is generally found via experimentation in a wind tunnel where the remaining variables can be controlled. Therefore, the lift equation is given by

$$L = \frac{1}{2}\rho V^2 S C_L \quad (1)$$

where L is the lifting force, ρ is the density of air, V is the relative velocity of the airflow, S is the area of the airfoil as viewed from an overhead perspective, and C_L is the lift coefficient.

As with lift, the drag of an airfoil depends on the density of the air, the velocity of the airflow, the viscosity and compressibility of the air, the surface area of the airfoil, the

shape of the airfoil, and the angle of attack. The complexities associated with drag and the airfoil's shape, angle of attack, the air's viscosity, and air's compressibility are simplified in the drag equation by use of the drag coefficient. The drag coefficient is generally found through testing in a wind tunnel, where the drag can be measured, and the drag coefficient is calculated by rearranging the drag equation

$$D = \frac{1}{2}\rho V^2 A C_D. \quad (2)$$

In the drag equation, D is the drag force, ρ is the density of the air, V is the velocity of the air, A is a reference area, and C_D is the drag coefficient.

3 Procedure

The donated wind tunnel used in this experiment was constructed out of cardboard, epoxy, and masking tape. The walls of the wind tunnel where the lid met the rest of the tunnel were lined with strips of soft foam, which acted to insulate the airflow in the tunnel from outside turbulence. The airflow velocity at the test section was found to be 14.4 m/s using a Dwyer Transparent pressure gauge.

Shown in Figure 3 are six different airfoils used in the experiment. Each airfoil was unique in camber and thickness so as to induce various lift and drag characteristics. The airfoils have similar chords, but it was difficult to produce precise sizes, the materials available were not ideal for airfoil construction. The material used as the base for



Figure 3: Airfoils used in the experiment. On the top from right to left are NACA 3314, NACA 8321, NACA 1209. On the bottom from right to left are NACA 6217, NACA 0014, NACA 5417.

the airfoil construction was a dense packing foam. An outline of the profile for each airfoil was transferred to the foam, and was cut using a band saw. This yielded the general form for each airfoil, but the surfaces were rough and uneven. Thus, the surfaces of each airfoil were sanded as smooth as could be perceived by the human eye while maintaining the original shape. A layer of transparent packing tape was then attached to the entire surface area to prevent airflow from piercing the airfoils. The six airfoils were NACA 3314, NACA 8321, NACA 1209, NACA 6217, NACA 0014, NACA 5417.

The wind tunnel allowed limited access to the test section, thus an apparatus was constructed around the existing condition of the test section to measure the lift and drag acting on the airfoil. On the floor of the test section were two small rectangular holes spaced 0.09 m apart, orientated perpendicular to the airflow. A Mettler Toledo PD3002-5 digital scale was placed beneath these holes in the hollow area under the test section. A wooden apparatus was constructed such that an airfoil could be held in the test section with a freedom of movement that allowed lift and

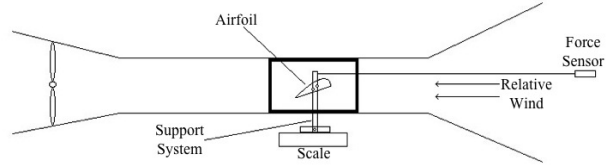


Figure 4: Setup of the experiment to measure lift and drag.

drag to be measured, and its base was fixed to the scale. In order to measure the drag force, a Pasco Scientific CI-6537 Force sensor was positioned a distance from the intake of the wind tunnel at a height equal to that of the support apparatus. A string was fixed to the support apparatus, while the opposite end of the string was suspended by a hook on the force sensor. When measuring force, the force sensor outputs a voltage. Using the DataStudio program, the output voltage was converted to a force with units in Newtons. The force of the string pulling on the hook of the force sensor was measured with and without an induced airflow, and the difference was found to be the net drag force. Figure 4 shows the basic setup of the experiment to measure lift and drag force acting on an airfoil. Two data runs were conducted for each of the six airfoils at an angle of attack of 20° where measurements were taken with and without an induced airflow.

4 Data and analysis

The difference between the measurements taken when the airflow was induced, and when it was at rest yielded the actual lift

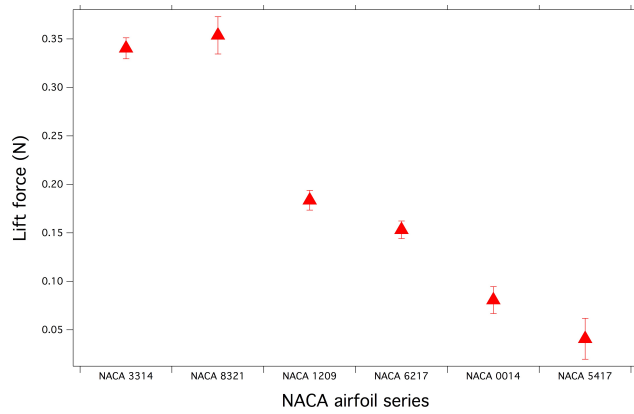


Figure 5: Graph of the lift force measured for each airfoil. The markers indicate the average force of the two data runs while the values each error bar extends to correlate to the measurements taken for each of the two data runs.

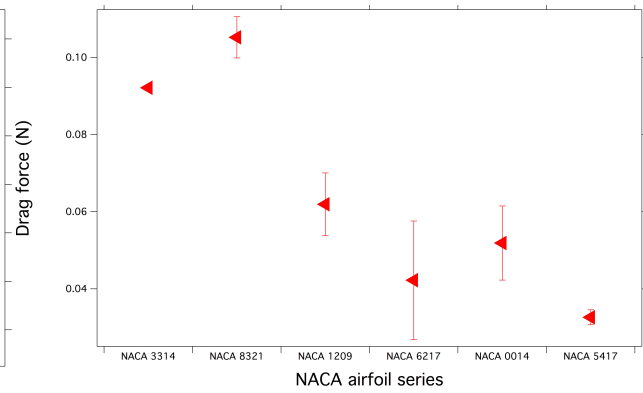


Figure 6: Graph of the drag force measured for each airfoil. The markers indicate the average force of the two data runs while the values each error bar extends to correlate to the measurements taken for each of the two data runs.

force of each airfoil. This was done for the drag force as well, but the force of drag of the support system was subtracted from the total, yielding the actual drag force for each of the the two data runs. The measured lift and drag forces of each airfoil are shown in Figure 5 and Figure 6 respectively.

Most of the airfoils performed as expected with the induced airflow given the low velocity relative to normal flight conditions. The NACA 3314 airfoil, with a deep camber and high thickness, is generally used for larger aircraft, such as transports or bombers. It is meant to generate a lot of lift at low speeds, which it was successful in doing. The NACA 8321 airfoil was expected to generate high lift at low speeds due to its deep camber and thin cross section. It was successful, producing more lift than any of the other airfoils. The

NACA 1208 airfoil is intended to be used at higher speeds on race planes, as well as military fighters or interceptors. Therefore, it is not surprising that it was not able to generate a lot of lift in a wind tunnel of low velocity. The NACA 6217 airfoil was expected to generate more drag than lift due to a deep camber and high thickness. However, it defied expectations producing a greater lift force than drag force. The NACA 0014 airfoil was symmetric in shape, and is not typically used in aircraft design. It produced medium lift and drag. The NACA 5417 airfoil was intended to generate less drag than lift due to the camber being located closer to the trailing edge. It produced the least amount of drag of all the airfoils. All references to high or low lift and drag of each airfoil are considered relative to the rest of the airfoils tested, because the

same flight conditions were applied for each.

5 Conclusion

This experiment demonstrated the aerodynamic forces of lift and drag that act on an airfoil. These forces occurred when a airflow was introduced to the area around various airfoils. This was done under controlled conditions through the use of a wind tunnel. As a result, the drag and lift characteristics for airfoils of varying geometries were successfully measured and compared.

The variation in measurements for each airfoil may have occurred, because errors in the design of the experiment. Typically, airfoils intended for wind tunnel experimentation are constructed by computer controlled machinery to ensure smooth and even surfaces. As the airfoil's in this experiment were formed by hand, it was difficult to produce even geometries. This led to an uneven fitting of the packing tape to the airfoils' surfaces, which became more deformed by the airflow due to the lower pressure created. Another error occurred via the string attaching the force gauge to the support system in the test section. When the airflow was introduced to the system, the string oscillated slightly. The obstruction of the string was not enough to disrupt the airflow at the airfoil, but it did affect the airfoil and the support system, causing difficulty in taking accurate measurements.

Future work could use a wind tunnel designed specifically for airfoil testing so that a better measurement system could be devised, and the angle of attack and airflow velocity

could be varied. A proper means for construction of airfoils would be useful as well.

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