

A Review and Study on Airfoils and Aerodynamics

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The study of aerodynamics is a constantly evolving field, often on the cutting edge of engineering and design. Aerodynamic study has massive implications in fields such as transportation and sport. One of the most fundamental shapes of aerodynamics is the airfoil, a device often responsible for crucial forces such as lift and downforce. In this study, we ran numerous experiments with the help of a digital wind tunnel simulator in order to explore and compile knowledge of several factors key to the design of airfoils. Our study included information on several different variables, including angle of attack, camber, thickness, shape, speed, and altitude, in order to document their impact on crucial factors such as lift and drag. Our study made several insights into maximizing the efficiency of various characteristics of airfoils and sought to explain many of the phenomena we observed by referencing established studies and papers. Ultimately, we hoped to provide a synopsis of airfoil design that was as useful to the layperson as it is to the engineer while providing a helpful reference for what continues to be a field at the forefront of science and design.

Introduction

One of the most important shapes to the function of transportation today is the airfoil. An airfoil is a teardrop-shaped device featuring two curved surfaces. Each of the surfaces has a different curve and camber¹, which serves to direct the airflow in specific ways around its shape². Airfoils are able to move through the air with efficiency similar to a teardrop, which is the most aerodynamic shape yet discovered. Instead of using airfoils to pass through the air efficiently, airfoils modulate the air around them while maintaining their efficiency. This is the primary reason why they are used in high-speed vehicles, as aerodynamicists are able to use them to create lift or downforce with minimal drag penalty. This has made airfoils common to aerospace (where they are found in the wings, rotors, and control surfaces of helicopters and airplanes), professional motorsports (for various downforce-generating devices), and even in marine transportation (where they are used to generate lift in hydrofoils).

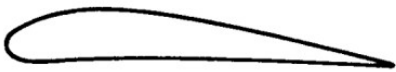


Fig. 1 Cross section of a cambered airfoil². (Image taken from Flight Without Formulae)

In order to modify and optimize airfoils for their various applications across different forms of transportation it is often necessary to modify their various characteristics. This includes modifications to many of the fundamental variables within air-

foils. For some applications, such as the takeoff and landing functions in most aircraft, it is necessary to increase the camber of an airfoil. This arches the shape of the airfoil and serves to increase lift, especially when drag may be of less importance. Similarly, the angle of attack can be modulated to increase lift when it is necessary, such as at low speeds. Controlling the angle of attack, in relation to a flat and level plane means that the same airfoil will be able to produce different amounts of lift at different stages in a flight. However, dramatically increasing the presence of lift comes with a significant drag penalty. Less common is the consideration of airfoil thickness, a property that also serves to increase lift and drag in conjunction with each other.

These properties, however, must be considered in their relation to other variables of flight, ones that cannot always be controlled by the shape of properties of an airfoil but are nonetheless important for their real-world applications. One example of this comes with altitude. It is well known that the air becomes less dense at higher altitudes, a factor that must be considered as both lift and drag decrease at the considerable heights that airplanes reach. Motorsport, too, is impacted by such changes in air density, as this variable impacts the characteristics of various circuits or locations. Similarly, speed will also change the characteristics of airfoils, typically by increasing both lift and drag. This change must be considered by aerodynamicists in order to predict flight or handling characteristics. Furthermore, engineers must account for form and parasite drag, which will both effectively hinder the efficiency of the vehicle and contribute to a substantial loss in performance. Form drag is the drag caused by the fundamental shape of the vehicle. In an airplane, the most likely culprit is the fuselage, while in motorsport, it tends

to result from the combination of cockpit and wheels.

The ultimate goal of this manipulation, whether the vehicle is a helicopter or a rally car, is to use the aerodynamic profile of the vehicle to optimize the fundamental forces of flight: thrust, lift, drag, and weight. In any vehicle, optimizing lift and reducing drag is crucial for successful performance and will serve alongside other forces (thrust and weight) to enhance or overcome their presence. This study will seek to use new tools to replicate many of the studies done in past years, contextualizing and compiling many of these previous findings. Part of our goal will be to prove the viability of accessible alternatives to conventional wind tunnel testing, using our extensive data collection to illustrate this point.

Literature Review

Many of the variables chosen in this study were examined and were well-researched in years past, and as a result, it is crucial to use such research to contextualize the current study.

Fundamental Forces of Flight

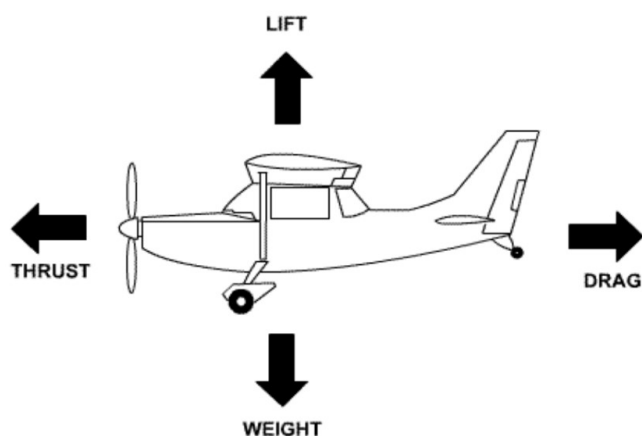


Fig. 2 Above, a visual representation of the fundamental forces of flight that all aircraft are subject to³. (Image taken from An Analysis and Survey on the Aerodynamics of F1 Car Design)

The fundamental forces of flight are thrust, lift, drag, and weight. Lift and weight are often considered vertical forces. In aircraft, lift serves to oppose the force of gravity³. In aircraft, the wings are responsible for producing this force while also mitigating the drag they inevitably produce³. The engines produce thrust and serves to move the craft forward, opposing the drag that is produced by the body of the aircraft³. These particular factors often serve to drive the shapes and functions of airfoils.

Bernoulli's principle describes the manner in which lift is generated. The most common example of this principle is the

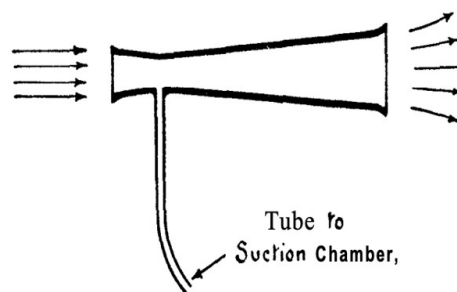


Fig. 3 The pictorial representation of venturi tube². (Image taken from Flight Without Formulae)

venturi tube. The Venturi Tube is a device, tubular in shape, that gradually narrows before expanding again before the air exits (see Figure 3)². The air passing through the tube, as a result of its unique shape, will speed up in comparison to the free-flowing air. This is a result of the neck of the tube, as the smaller cross-section will force the air to speed up as it travels through the tube. Bernoulli's principle explains that with the increasing speed of the airflow, the force exerted on the inside of the tube is decreased. The opposite is true as the speed decreases; the pressure on the tube's walls will increase². The faster-flowing air is not able to exert as much force on the wall of the tube as its slower-moving counterpart.

Airfoils exploit this principle to great effect. The top of an airfoil is shaped specifically to be a longer distance than the bottom of the airfoil. As it moves through the air, particles traveling over the top of the wing will have to travel a further distance than the ones on the bottom. As a result, they are sped up and exert less force on the top of the airfoil than their counterparts on the bottom. From Bernoulli's principle, higher wind speed corresponds to lower pressure, assuming the same head. Since more pressure is present below the airfoil compared to the upper surface based on the relative wind speeds, the airfoil is pressed upwards, generating lift. The equation for Bernoulli's Principle follows:

$$p + \frac{1}{2}\rho V^2 = \text{const} \quad (1)$$

p - pressure
 ρ - density
 V - velocity

Angle of Attack

One of the most important variables in the realm of flight is the angle of attack. The angle of attack refers to the rotation of the airfoil in reference to a flat and level plane, as demonstrated in Figure 4. Increasing the angle of attack typically results in both increased lift and increased drag, a pattern that remains true up until about 15 degrees of rotation (see Figure 6 and Figure 7).

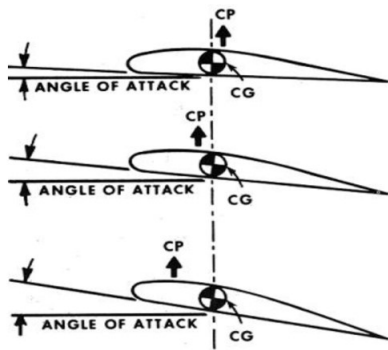


Fig. 4 Angle of attack is the angle formed by a chord running the length of the wing section and a flat surface. Several different angles of attack are displayed. A more aggressive angle of attack results in a center of pressure that is farther forward³. (Image taken from An Analysis and Survey on the Aerodynamics of F1 Car Design)

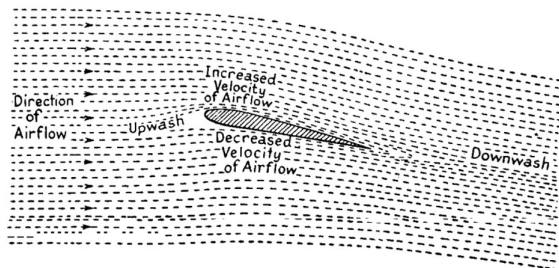


Fig. 5 The angle of attack is demonstrated above in a symmetrical airfoil. The shape of the airfoil, combined with the angle of attack, creates a downwash, increasing lift². (Image taken from Flight Without Formulae)

In aircraft, the angle of attack is often modulated during take-off and landing to produce more lift at lower speeds, especially as the resultant drag penalty is less consequential. Similarly, in motorsport, the angle of attack is used to increase or decrease the amount of downforce acting on a vehicle for different applications across different circuits or categories. Altering the angle of attack does not change the forces at work in Bernoulli's Principle but rather comes as a result of changing upwash or downwash. Indeed, the effect of the angle of attack is often dependent on the shape of the wing being rotated.

Camber and Thickness

Airfoils are often manipulated to produce more or less lift to suit different functions. Two of the most common ways of doing this are through the manipulation of the camber and thickness of an airfoil. Camber is a measure of the curvature introduced to the airfoil when observing its cross-section. Typically, increased camber will dramatically increase lift. However, drag too, increases dramatically with the camber². The thickness of

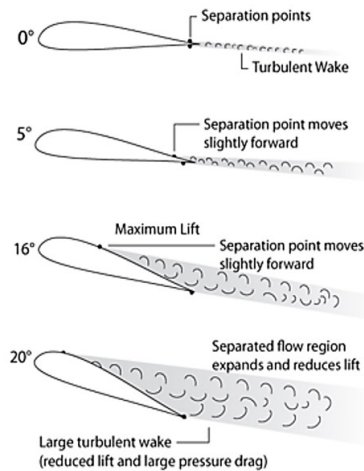


Fig. 6 The above figure demonstrates why increasing the angle of attack beyond 15-18 degrees reduces lift and increases drag. A higher angle of attack leads to flow separation, which reduces the performance of the airfoil³. (Image taken from An Analysis and Survey on the Aerodynamics of F1 Car Design)

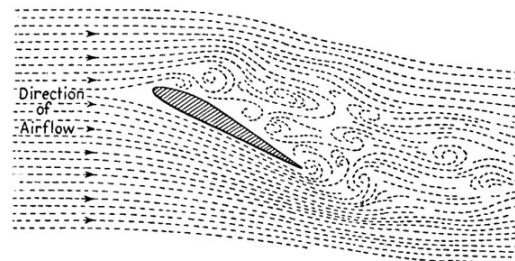


Fig. 7 Figure 7 demonstrates the flow separation that results from an excessive angle of attack². (Image taken from Flight Without Formulae)

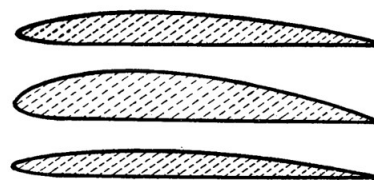


Fig. 8 Above, three airfoils of varying camber². (Image taken from Flight Without Formulae)

the airfoil will have a similar, though less pronounced, effect on lift and drag. This is because an increased thickness will cause air to flow faster over the top of the airfoil, increasing lift². However, increasing thickness will also increase the distance the air must travel over the bottom of the airfoil, meaning the effect will be less pronounced than camber. Furthermore, the increase in drag will require more thrust to maintain the desired

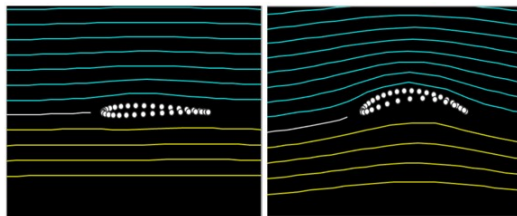


Fig. 9 FoilSim-generated images display the difference between airflow around a lightly cambered and highly cambered airfoil. The increased downwash and faster airflow yield more lift in the more cambered foil.

speed, thus inhibiting the efficiency of this method.

Effects of Altitude

Factors external to the aircraft or airfoil must also be considered in the discussion of their properties. Many modes of transportation are often challenged by varying altitudes, which force adaptation of the aircraft's aerodynamics. It is well-known and documented that air pressure decreases with altitude, becoming less and less dense the further it gets from Earth's crust². This has a significant effect on engineering, as the thickness of the air is directly related to the amount of lift and drag that it is capable of producing². Denser air produces more lift, at the penalty of more drag².

Effects of Speed

Similar to this principle are the effects of speed on aerodynamic performance. Increased speed also produces increased levels of lift and drag, but in a far less linear fashion than a variable such as altitude. This is demonstrated through the force required to power an object at a certain speed. To double the speed would require four times the force. This pattern continues and has thus been dubbed the "speed-squared law," with drag being proportional to the square of speed ($D=V^2$).

Types of Drag

Aircraft produce several different types of drag, including induced drag, form drag, and skin friction. Induced or active drag is the drag generated by the plane's wings and, as a result, is inherent to flight. The generation of lift, and therefore flight itself, requires that this drag be produced. As a result, this drag cannot be entirely eliminated. Conversely, other types of drag are, in fact, able to be reduced to near-infinitesimal quantities. Form drag, for example, arises from the imperfections on the body of an aircraft, which differ based on the plane's purpose and function². This could include external fuel tanks, instruments, tails or control surfaces, weapons, or wheels². Many of these parts, as aeroplanes have developed, have been streamlined

or eliminated altogether. Fuel tanks have been made internal, and so have wheels and landing gear. Both of these changes to modern aircraft have served to make them more efficient. The final type of drag that aerodynamic engineers seek to eliminate is skin friction. Skin friction is caused by uneven or rough surfaces as they travel through the air. Modern aircraft have smoothed surfaces, often made out of metal and smoothed with paint. This has replaced previous designs, which often included canvas fuselages, which were subject to large quantities of skin friction. Today, aircraft are constructed out of smooth aluminum or plastics, both of which are capable of achieving extremely low drag.

The Coanda Effect

Observing the flow patterns around the airfoils shown in Figures 5 and 7 raises an interesting question. The flow on the top surface of the airfoil bends around it, just as the bottom flow, seemingly without motivation for doing so. This phenomenon can be explained by the Coanda Effect. The Coanda Effect explains that a fluid discharged from an orifice will have a tendency to cling to a surface near the orifice it exited. The same principle is observed on airfoils, as air moving over the top of the wing section will stick to the airfoil's upper surface⁴.

Methods

Over the years of innovation in flight and flight technology, many methods have been used to test aerodynamic performance. In the modern age, the preferred method of study is typically conducted by way of wind or smoke tunnels. A wind tunnel is a device where a series of fans, typically driven by electric motors, drive air through a large tube or tunnel². The supported model resides in the center of the tunnel². The ultimate goal of the contraption is to simulate the airflow experienced by a moving object, as the moving air will have the same over the stationary wing section will have the same effect as stationary air on a moving wing section².

In different cases, a variety of models can be used to test for different variables. Often, scale models of aircraft are tested, which lends engineers useful insights into the performance of their vehicles. Aerodynamicists often use sensors or visual cues (such as a string) in order to understand the airflow over the bodies and gather data from the airflow. In other cases, a single portion of a vehicle might be tested, such as a wing or fuselage, a result that often stems from the inherent (size) limitations of such tunnels. Wind tunnels must be significantly larger than the models being tested, or else the proximity to the tunnel walls will interfere with the aerodynamics of the model, yielding errant results.

In similar fashion, a smoke tunnel is another device that can be utilized to optimize vehicular aerodynamics. It serves a purpose

very similar to wind tunnels, but the presence of smoke can help scientists better observe the airflow around their vehicles. Smoke tunnels are, therefore, superior to wind tunnels in this visualization. Better yet, the presence of smoke rarely skews aerodynamic performance, as it behaves nearly identically to its aerial surroundings.

This study, however, uses virtual tools as an alternative to the complications and costs of running a functioning wind tunnel. Our tool is called FoilSim, and it is a simulation developed by NASA specifically for the testing of airfoils. FoilSim allows researchers to provide important variables in order to gather a specific data set. Variables such as speed, thickness, camber, and angle of attack are all synthesized within the simulation to output important data, especially lift and drag. For the majority of our simulations, our alterations were kept to a minimum and kept the simulation to its default settings. Size, speed, and altitude were kept constant throughout the experiment, unless they were tested directly. angle of attack was set to 0 degrees (unless otherwise tested), while the airfoil maintained a camber of 2. Chord thickness was kept at the default of 10.5.

The tool is incredibly efficient for gathering large quantities of valuable data. However, it is important to acknowledge the fundamental limitations of this method of testing. The most blatant is the tool's use of a two-dimensional plane rather than a three-dimensional space consistent with a typical wind tunnel. Additionally, the effects of all the different kinds of drag are possibly not included in these simulations. This limitation provides less quantitative information. These factors hindered our understanding of the airflow as a whole and contributed to some gaps in our knowledge. Furthermore, the limited amount of data available using the tool meant that we were not able to test all relevant values (such as greater speed or degrees of angle of attack), but instead were limited to a preset. These factors had the unfortunate result of constraining different areas of our research. However, forgiving these flaws unlocks an incredible amount of usable and reliable data relevant to a trend-based qualitative study.

Results and Discussion

Ultimately, our data proved to be consistent with much of the data that was collected from other scientists and aerodynamicists previously². Our data was collected using FoilSim, a newer and cheaper way of such data collection suitable for learning. Much of the data replicated other studies' well-tested results, proving my online means of data collection to be reliable on the whole. This was proven across the entirety of the graphs that will be analyzed, thus proving FoilSim to be worthy of our trust. In the following paragraphs, I will analyze the results of the testing process by providing a more in-depth review of the results, discuss the data's relation to the graphs generated in other studies, and pinpoint the causation for many of the

phenomena that we have observed throughout the experiments.

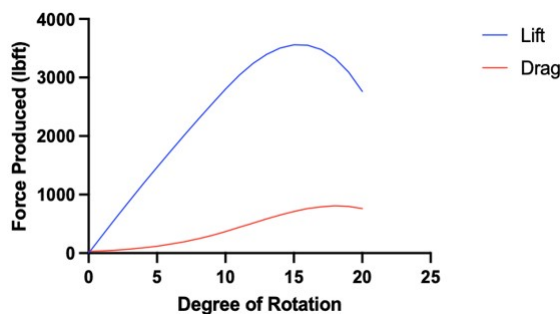


Fig. 10 Comparing the lift and the drag produced by an increasing angle of attack in a symmetrical airfoil. We used a FoilSim to gather (lift and drag) data across twenty degrees of possible angle of attacks. Lift was generated most effectively at around a fifteen-degree angle of attack, while drag peaked at around eighteen degrees. This was entirely consistent with the results that were referenced in Flight Without Formulae, with both studies finding that lift was maximized around fifteen degrees of rotation.

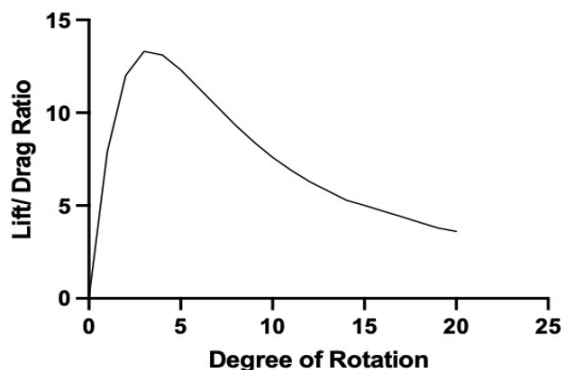


Fig. 11 Angle of attack's effect on the Lift to Drag Ratio in a symmetrical airfoil. We found that this ratio was maximized at three degrees of rotation.

Discussion of Angle of Attack

Figure 10 and Figure 11 demonstrate the relationship between the angle of attack and the lift and drag produced by an airfoil. Through Figure 10, we observed that lift increased constantly until the angle of attack reached around fifteen degrees. The same relationship was observed in "An Analysis and Survey on the Aerodynamics of F1 Car Design," where lift similarly tapered off after reaching the critical angle of attack. Flow separation is at the root of the drop-off in lift. As demonstrated in Figure 7, there is a point where the airflow traveling over the top of the wing will no longer be able to remain in contact with the upper surface of the wing. Instead of "sticking" to the

upper edge of the wing, the air begins to spiral and eddie (to swirl or rotate in the wake of a moving object, forming vortices), leading to a significant loss in aerodynamic performance. The loss in performance can be put down to a loss of downwash. Flight Without Formulae explains that more air will be deflected downward as the angle of attack becomes more extreme². The downward-deflected air will have an opposite effect on the wing, which will be pushed upward, generating lift². With less downwash, there is less upward pressure on the wing, meaning that angles of attack beyond fifteen degrees will no longer benefit from an increasing amount of available lift.

Figure 10 also revealed that drag would cease to increase beyond the fifteen-degree angle of attack, likely due to the same principle of flow separation. We hypothesize that as the angle increased, the two distinct airflows remained separated, meaning that further increases in the angle of attack did not have a dramatic impact on the amount of drag produced, as it simply prevented the flows from mixing.

Figure 11 serves to reveal the lift/drag ratio present across the range of angle of attack values. It found that the ratio was maximized at three degrees of rotation. This was owed to the fact that, beyond three degrees, the amount of lift continued to rise steadily while the amount of drag produced increased even faster.

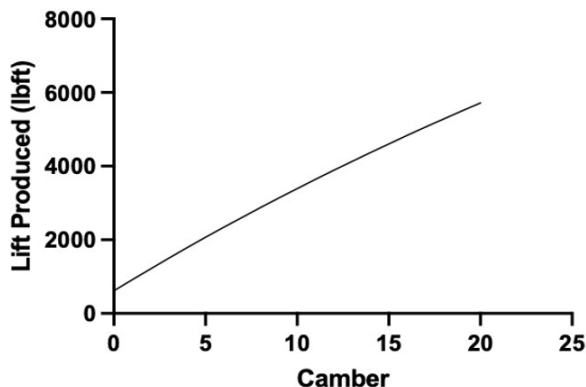


Fig. 12 Effect of camber on the lift produced by an airfoil (angle of attack set at two degrees). Lift increased consistently as camber increased.

Discussion of Camber

We can observe several takeaways from the figures comparing lift and drag to camber. Figure 12 demonstrates that lift consistently increases with camber but that the growth will show signs of slowing as more camber is introduced. Figure 13 demonstrates a similar effect, as drag grows constantly with camber. However, rather than showing signs of slowing down, the amount of drag produced will, in fact, begin to increase

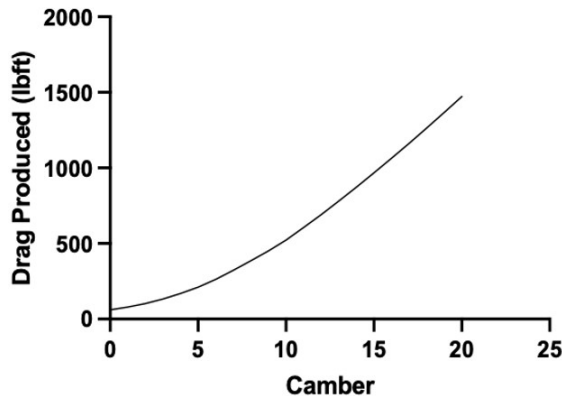


Fig. 13 Camber’s impact on drag in an airfoil with an angle of attack set to two degrees. FoilSim was used to simulate the impact that increased camber had on the drag produced. Drag increased more quickly as the amount of camber increased.

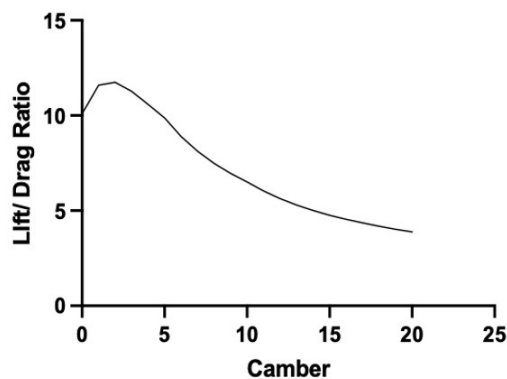


Fig. 14 Simulated effect of camber of the lift-to-drag ratio of an airfoil (angle of attack has been set to two degrees). A slightly cambered airfoil was found to be most effective at maximizing the lift-to-drag ratio.

faster and faster as more camber is introduced.

Figure 14 revealed that a small camber is, therefore, most effective for maximizing the lift-to-drag ratio. With drag increasing more and more rapidly but lift increasing steadily, the ratio will continue to fall off as more camber is added to the airfoil. This makes the slightly cambered airfoils ideal for normal flight conditions, while the cambered ones can be utilized when maximizing lift is important, but drag is less of an important factor. Because this often is the case at lower speeds, camber will often be added to airfoils upon takeoff and landing in order to get off the ground quickly, or safely lose speed.

Discussion of Negative Angles of Attack

Figure 15 served to display the fact that it is possible for an airfoil to generate lift, even at a negative angle of attack. The

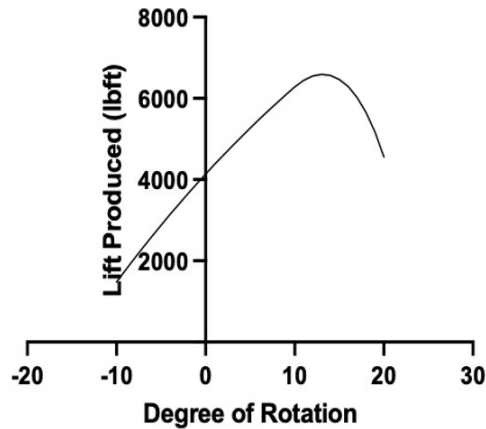


Fig. 15 Angle of attack's effect on the lift produced by a cambered airfoil in a simulated wind tunnel. FoilSim was used to simulate the results of a wind tunnel. The cambered airfoil was able to produce lift even with a negative angle of attack, as has been noted in previous studies. The amount of lift produced increased until it began to decrease at an angle of attack of thirteen degrees.

data demonstrated that the cambered airfoil was able to maintain these properties better than a non-cambered one, given its unique shape. It's curved surfaces are able to divert the airflow more effectively than the non-cambered airfoil. This is observed in Figure 9, which demonstrates the cambered airfoil's ability to more dramatically manipulate the air.

Through the data we collected, it was also possible to observe that the angle of attack at which the maximum lift was generated was actually lower than the non-cambered airfoil (13 degrees vs 15 degrees). This was likely due to the fact that the camber produced a more angled upper surface of the airfoil, expediting the onset of flow separation and increasing the presence of eddies formed (see Figure 7).

Discussion of Form Drag

Figure 16 compares the drag generated by several shapes. Rotated to twenty degrees, we found that the airfoil, cambered airfoil, and flat plane generated similar levels of drag, given their similar profiles at that angle. The highly cambered airfoil, on the other hand, introduced more drag because the trailing edge was contrary to the direction of the wind. The cylinder produced the least drag out of all the shapes, given that it was closest to the teardrop shape at the 20-degree angle of attack.

Discussion of Speed

Figures 15 and 16 explored the impact that increasing speed had on the aerodynamic performance of an airfoil. As speed increased, the lift and drag increased proportionally, with each producing dramatically more force at high speed than at low

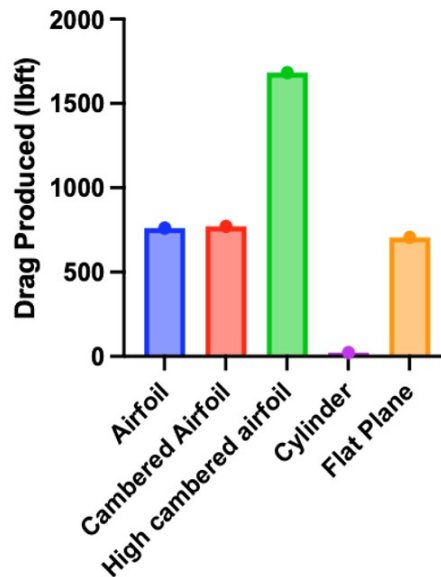


Fig. 16 Comparing the form drag across several different shapes in a virtual wind tunnel. The experiment used FoilSim to record the drag of several different shapes (set to maximum angle of attack) at a simulated speed of 100 miles per hour. The experiment found the highly cambered airfoils to be the most aerodynamically inefficient and the cylinder to be the most efficient.

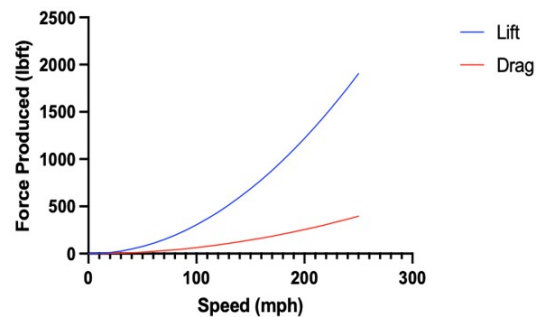


Fig. 17 Simulated effect of the lift and drag produced by increasing the rate of airflow over a symmetrical airfoil. The test used FoilSim to set a symmetrical airfoil at a two-degree angle of attack as the simulated speed increased. Both lift and drag increased rapidly with speed.

speed. Indeed, as expected, the amount of force produced rose exponentially with the increase of speed, mirroring the findings referenced in Flight Without Formulae. However, despite the relative consistency of the lift-to-drag ratio, it was found to increase slightly as more speed was applied, meaning the airfoil was more aerodynamically efficient at high speed.

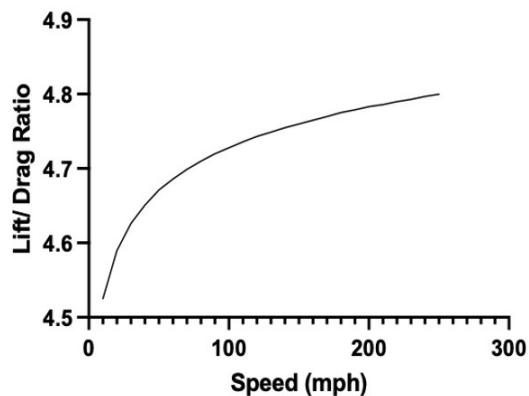


Fig. 18 Comparing speed to the ratio of lift and drag generated by a symmetrical airfoil. FoilSim was used to set the angle of attack to two degrees and gradually increase the speed in order to observe the change in the lift-to-drag ratio. Overall, the ratio stayed largely consistent despite the considerable increase in speed.

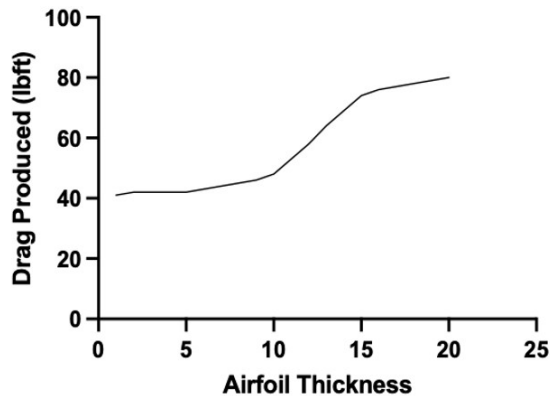


Fig. 20 Correlation between the thickness of an airfoil and the drag it produces at an angle of attack of two degrees. The experiment utilized a virtual wind tunnel to plot the relationship. The drag produced increased steadily from a thickness of zero to a thickness of ten and rapidly from ten to fifteen before the growth slowed once more.

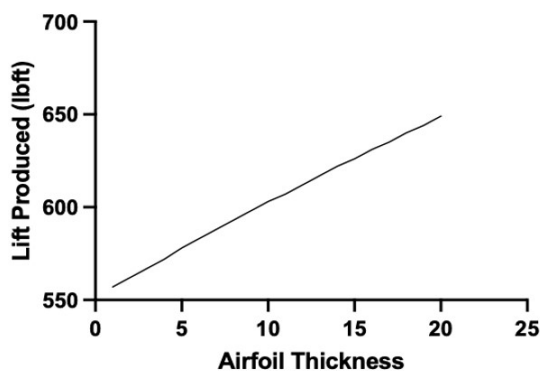


Fig. 19 Simulated effect of the airfoil thickness on the lift produced by the airfoil. Lift was found to increase steadily but slowly in tandem with the airfoil's thickness.

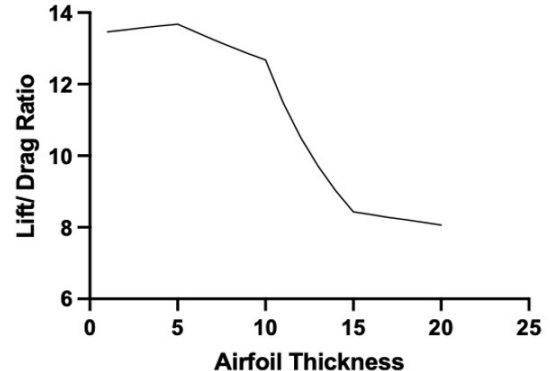


Fig. 21 Testing the thickness of a symmetrical airfoil against it, resulting lift-to-drag ratio. The ratio decreased as the thickness increased on the airfoil.

Discussion of Airfoil Thickness

Figure 19 and Figure 20 outlined the impact that increasing airfoil thickness had on the lift and drag that the airfoil generated. Because the test was done on a symmetrical airfoil, where no lift would be produced at an angle of attack of 0 degrees, the angle of attack was set to 2 degrees. Figure 19 demonstrates that the lift rises steadily as the airfoil's thickness increases. When set at even the slightest angle of attack, the thicker airfoil means that the air must travel a further distance over the top of the airfoil than over the bottom of the airfoil. In accordance with Bernoulli's principle, this will create less pressure on top of the airfoil than on the bottom, which serves to increase lift. Ultimately, the increase in thickness had a similar effect to increasing the camber of the airfoil, as both manipulate the distance the air must travel over the airfoil's top edge.

Similar to camber, drag would also rise with the increased thickness, as this exposed a larger area to the wind. Interestingly, however, the drag did not increase exponentially or linearly. Instead, the drag increased slowly from zero to ten units, before rapidly increasing from ten to fifteen. This trend would not continue, however, and the amount of drag produced began to rise more slowly again, fifteen to twenty.

This fascinating pattern had substantial consequences on the pattern displayed in Figure 21. Because of the pattern of drag, the Lift to Drag Ratio would display a similar trend in the other direction. The Lift to Drag Ratio rose slightly from zero to five, as the increased lift outweighed the drag penalty incurred by the thicker cross-section. From five to ten units, the Ratio decreased slowly as the drag began to outweigh the ever-increasing lift. The Ratio would decrease significantly from ten to fifteen units, owing to the massive spike in the amount of drag produced by

the widening airfoil. The decreasing rate would eventually begin to level out again toward the tail end of the graph. Figure 21, therefore, demonstrates that a thickness of five would ultimately be the most efficient for generating lift (and minimizing drag).

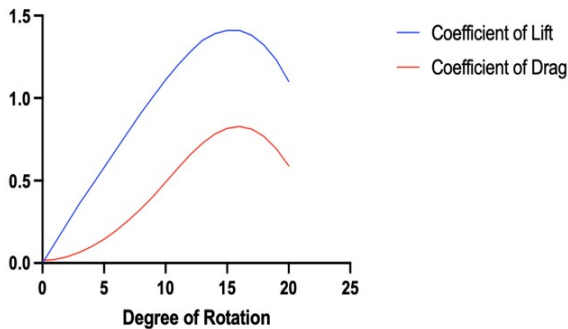


Fig. 22 The chart displays the relationship between the angle of attack and the coefficients of lift and drag produced in airfoils. The coefficients of lift and drag both rose before peaking at a maximum angle of attack of sixteen degrees.

Discussion of Angle of Attack vs. Lift and Drag Coefficients

Figure 22 demonstrates the relationship between the angle of attack and the coefficients of lift and drag that were produced. The coefficient of lift grew steadily, while the coefficient of drag increased more dramatically after about 2 degrees of rotation. Both coefficients peaked at a 16-degree angle of attack, before they were reduced again.

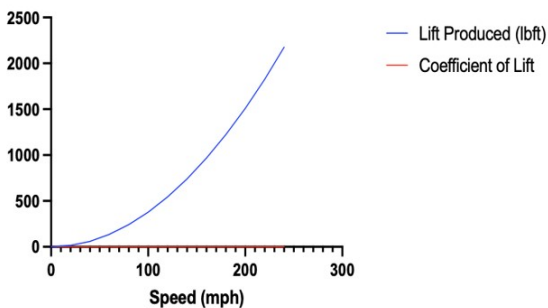


Fig. 23 Comparing the coefficient of lift to the amount of lift produced as speed is increased over a cambered airfoil. The data was plotted with the help of FoilSim, which was used to compare the quantity of lift to its coefficient. We found that speed increased the amount of lift produced but did not alter the coefficient of lift at any point.

Distinguishing Lift and Coefficient of Lift

In Figures 21 and 22, the coefficient of lift for two different airfoils was compared to the total lift they produced. The graphs

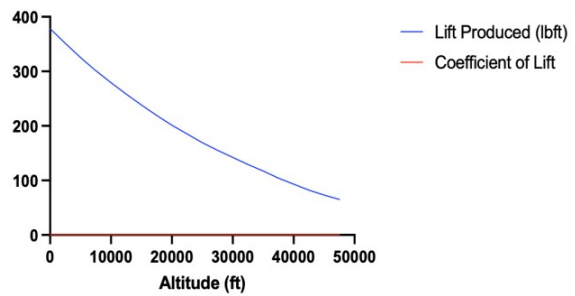


Fig. 24 Simulated effect of altitude on the lift produced and the lift coefficient in a cambered airfoil. The data was documented using FoilSim, with the airfoil subject to speeds of 100 mph. Similar to the plot of speed, the coefficient of lift stayed constant, even as the altitude increased and the lift decreased.

serve to demonstrate that external factors such as speed and altitude matter for the airfoil’s output but do not have an impact on the coefficient of lift. The same pattern can be observed for the amount of drag and the associated drag coefficients.



Fig. 25 The above diagram shows the airflow over a flat plane. The presence of the vortices along the upper surface of the plane reveals that flow separation has led to a loss in lift efficiency. An ideal model would display two synchronized airflows and the elimination of the vortices. A similar characteristic can be observed in airfoils whose angle of attack exceeds its most efficient state². (Image taken from Flight Without Formulae)

Discussion of Flow Separation

Figure 25 is a visual representation of flow separation over a flat plane. Flow separation occurs when the angle of attack becomes too great and starts to have a negative impact on the amount of lift produced. As demonstrated in the image, when the angle of attack becomes too great, the airflow will separate from the airfoil, and the resulting vacuum generated by the separation will cause eddies atop the airfoil. This significantly reduces the amount of downwash that the airfoil can produce, which ultimately leads to less lift being produced.

Conclusion

Through this study's research and experimentation, we were able to effectively summarize, explain, and compile several of the aerodynamic phenomena that are observable within the context of flight, transportation, and airfoils. Crucially, we used new tools to replicate old experiments and found success in reproducing and connecting the results of our experiments to those done by others with differing methods. Our study serves as a comprehensive analysis of the workings of airfoils and is important to understand them in their relationship to various types of transportation and motorsport. It provides valuable insights for all sorts of people to build a better understanding of the workings of aircraft while remaining relevant to scientific research and inquiry.

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