AIRFOILS AND LIFT

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ABSTRACT

The topic of this report is the forces experienced by a 2-D cross section of an airfoil extended symmetrically into 3-D. With a given shape of airfoil, whether it be a plate or some more advanced design, the quantities of lift and drag can be measured in a wind tunnel for a given wind speed and angle of attack. Lift is linearly related to angle of attack up until the stall angle and is quadratically related to wind speed. In 1799, Sir George Cayley identified the four forces working on a body in flight, lift, drag, thrust, and gravity. The lift component of force generated by pressure distributions around the body must be greater then the gravitational force on the whole plane to maintain altitude. A real airplane has many design factors, only one of which being the wing, and a real wing is not symmetric along its span. Lift profiles of a plate, a symmetric airfoil, and a cambered airfoil are measured with respect to angle of attack and plotted. The linear relationship with angle of attack is evident for the airfoils, the stall point is well displayed, and the quadratic relationship with lift to airspeed is confirmed. Camber increases the lift experienced at all angles and a basic airfoil design produces more lift then a plate for angles greater then 15 degrees. Drag is not measured, due to mechanical complications, but would significantly contribute to interpretation of the benefits and pitfalls of different shapes.

1. HISTORICAL BACKGROUND

Human interest in flying has a long history. Inspired by observations of birds, homosapians have been attempting to lift off, or fall slowly, for over 2000 years. The Chinese started using kites for ceremony and fun in 400 BC, but attempts to extend flight to humans often ending in death or grievous harm after jumping off a cliff with crude wings or a glider. Birds can fly with wings, so why not humans? This long era of unstructured exploration continued until the renaissance, when Leonardo da Vinci spent time rigorously studying flight and drawing his theories. This accumulated in his Ornithopter, a design he drew of how man might fly. It was never built or tested at the time. In 1783 the first balloon was built and flown while carrying human passengers. Hot air balloons are a simple way to lift the weight of people using pressure difference, and are without means of control beyond heating air or releasing. Sir George Cayley worked for 50 years between 1799 and 1850 building and then improving the gliders he built. His finalized contraption was able to fly with a young boy as pilot, after improving over the years with better wing shape and added tail for control.

Here begins the transitions from aeronautics into aerodynamics. Work previous was based on observation of the natural world and the crude understanding of physical principles that was available. A more rigorous exploration into fluids and flight was taken by Otto Lilienthal, a German engineer, who studied aerodynamics and worked to design a glider. He succeeded and published a book on aerodynamics in 1889. After more than 2500 test flights, he died in a crash were sudden strong winds caused him to stall and his landing broke his neck. He was the first person to make well documented, repeated, successful gliding flights. Samuel Langley worked to include powered propulsion in the later days of Ottos work, and created a model aerodrome powered by a miniature steam engine. In 1894, Octave Chanute published *Progress in Flying Machines*, a collection and analysis of all the technical knowledge he could find. All of this progress finally accumulates in the work of the Wright brothers, Orville and Wilbur. Their deliberate and methodical work took them from gliders to planes, using the above published books as well as a wind tunnel they build and the empirical data they collected. The first Flyer lifted off in December 1903, a 600 pound powered and manned biplane.

From the Wright brothers onwards, progress was rapid and motivated. Once the principle was demonstrated that man could fly, empirical data and theoretical development in fluid mechanics allowed substantial improvements. Historical motivators like WWI and WWII profoundly impacted the development of flight. The sustained arms race of the Cold War applied pressure for research into the military demands of aerodynamics. Modern military and commercial pressures continue to push development.

2. MATHEMATICAL THEORY

The two dimensional cross section of an airfoil wing can be studied in a rigorous mathematical manner. In 1906 Frederick William Lanchester published the first part of his two volume work Aerial Flight, in which he developed his model for the vortices that develop behind a wing. Around the same time, and independently, Martin Wilhelm Kutta and Nikolay Yegorovich Zhukovsky also developed theories that connect circulation to lift. In Zhukovskys work, the dependence of lift on velocity and circulation around the body is explicitly made. In 1904, Ludwig Prandtl delivered his groundbreaking paper Fluid Flow in Very Little Friction in which he describes the boundary layer and its importance on drag and streamline. These papers and publications are examples of how mathematical rigor could be applied to a real world problem with tangible results.

With a velocity field $\vec{u} = u(x, y)$ filling a two-dimensional space, a closed curve C is defined with circulation

$$\Gamma = \int_C \vec{u} \bullet d\vec{x} = \int_C udx + vdy \tag{1}$$

where the fluid is inviscid. It can be shown that for a thin and symmetric wing, of length L, making an angle α with the oncoming stream, then

$$\Gamma = -\pi UL \sin \alpha \tag{2}$$

which, combined with the Kutta-Joukowski Lift Theorem, gives the lift Λ

$$\Lambda = -\rho U \Gamma = \pi \rho U^2 L \sin \alpha \tag{3}$$

which for small angles α can be approximated by $\sin \alpha = \alpha$. This derivation is from D.J. Acheson's *Elementary Fluid Dynamics*.

3. AIRFOIL DEFINITIONS AND DIAGRAMS

The direction of air flow $\vec{U}$ far away from the airfoil defines the $\hat{x}$ direction as shown in drawing 1, perpendicular to which is the $\hat{y}$ direction. The lift force is the component of the total force felt by the airfoil in the $\hat{y}$ direction and the drag force is the component in the $\hat{x}$ direction (drawing 2). The airfoil in drawing 3 is symmetric about the x axis. Line AB from tip to tail is defined as the cord line, while the top curve is $f_T(x)$ and bottom curve is $f_B(x)$. This shape can be described with a max thickness of 10% at 22% of the cord. In drawing 4 the angle that the cord line makes with the x axis is the angle of attack α. If the mean line (*camber line*) is drawn $g(x) = (f_T(x) - f_B(x))/2$ for the symmetric airfoil it would be the same as the cord line. However, drawing 5 displays the same airfoil but with a 5% camber at 49% of the cord. Here the thickness at each point of x is kept constant to that in drawing 3, but the camber line deviates from the cord line to give the airfoil curvature.

4. APPLICABILITY OF WIND TUNNEL RESULTS

A mathematical theorem makes assumptions on the ideal nature of the fluid flow. To take an experimental stance on exploring airfoil shapes a wind tunnel can prove invaluable, however the direct application of results to full scale models is unreasonable. The first was created in 1871 and the Wright brothers made extensive use of one they built to improve their airplane design. The quality of the fluid flow is essential, and important developments have been made in wind tunnel design. Large and more powerful wind tunnels allow tests of larger models and at higher speeds. The Reynolds number is an important dimensionless quantity in fluid mechanics and is used to define the region of applicability for results. Defined as $\rho UL/\mu$, with ρ the density of the fluid, U the stream velocity, L a length characteristic of the body, and μ the coefficient of viscosity of the fluid, the Reynolds number needs to be of similar magnitude for experimental data to translate from scale models to full size creations. Larger wind tunnels allowed for large L, faster wind tunnels allow for higher U, and so the Reynolds number of the experiment can come closer to that of the full scale but interpretation of results is still difficult. Taking measurements of the full sized plane would remove this problem, and so ways to measure pressure along the wing were developed to study where the boundary layer might separated on a real plane in real conditions. Using approximate values for this experiment, a speed of $U = 18m/s$, density of air $\rho = 1.225kg/m^3$, $L = 0.15m$, and $\nu = 1.789 \times 10^-5kg/m/s$ gives a Reynolds number of 1.8×10^5.

5. EXPERIMENTAL PROCEDURE

Using two identical metal silhouettes of a selected airfoil design, a Styrofoam block is cut into a 3-D airfoil. A hole is drilled along its axis of symmetry at the 2-d center of mass of the silhouette. A rod through this provides the axis of rotation at Pivot B in Figure 1. The airfoil can then be pinched between two jaws of the apparatus shown in Figure 1, tight enough that it will not pivot from torques felt from airflow. The angle of attack can by changed by rotating the airfoil around this pivot and then fixing its orientation. Three airfoils were explored; the symmetric airfoil Bell 540, a 5% camber version of the same airfoil designed with Profili 2 that kept the same cord length of 15 cm and 1.5 cm thickness at its maximum, and a plate of thickness 2.5 cm and the same cord length. These are shown in Figure 4.

To obtain a force of lift measurement, each airfoil was positioned just outside the wind tunnels mouth by the apparatus in Figure 1. This frame sits on a scale and the change in weight measured by the scale gives the lift force countering gravity. The scale is zeroed without air flowing over the airfoil and the change in weight measured Δm by the scale with air flow is multiplied by the gravitational constant at the surface of the earth $g = 9.81m/s$) to give the force of lift,

$$\Delta mg = F_L. \tag{4}$$

Airspeed over the airfoil could be varied by changing the power of the wind tunnel. Measurements of the wind speed were taken using an anemometer before the airfoil was placed at the mouth when ever the fan was restarted or changed. The air flow out the mouth is assumed steady after some start up period.

The angle of attack of the airfoil was easily varied using the apparatus. For each measurement of lift, a picture was taken side on of the airfoil with a weighted string hanging behind to define the vertical. The wind tunnel level was checked, and assuming the air flows horizontally out of the mouth, then the direction of drag force can be defined as perpendicular to the line of gravity (Figure 2). Using Logger Pro, each picture was imported and a triangle drawn using the measurement tool (Figure 3). The length of each side allows the law of cosines to be applied to discover the angle β.

$$\cos \beta = \frac{B^2 - A^2 - C^2}{-2AC} \tag{5}$$

The angle of attack α is obtained by the relation $\alpha = 90 - \beta$.

6. RESULTS AND ANALYSIS

The force of lift was measured for the 5% Camber Airfoil at 3 angles and 3 wind speeds, the results plotted in Graph 1. Because only three points of angle were taken, and all well bellow the stall angle, no stall point is evident. All three demonstrate the linear relationship to angle of attack expected. Even with the limited number of points, the three data points clearly conform well to a linear relationship. To remove the dependence of lift on U^2, each point is divided by the appropriate U^2 (Graph 2). At each angle, the lift generated at different speeds collapse onto each other.

For each of the three shapes, lift was measured at different angles of attack for a single airspeed of $18m/s$ (Graph 3). All three display the stall point developing around 40 degrees. The two airfoils maintain the linear relationship with angle of attack up to the stall point, with the 0% camber airfoil's data points staying close to the fit line and the 5% camber having some noticeable deviation. The plate lacks the linear relationship with angle of attack.

Comparing the 0% camber to the plate, both have similar lift in the first 15 degrees but separate at higher angles where the lift generated by the airfoil is clearly higher. The 5% camber airfoil shows a greater lift at all angles, but suggests a slightly earlier stall point. It should be noted that this is not a 'thin' plate, in fact it is thicker then the airfoils. Having a plate of the same thickness as the airfoils, or an even thinner plate would have been more suitable.

7. DISCUSSION

The quality of air flow out of the wind tunnel could have been investigated. The measured wind speed at the mouth would vary by $\pm 0.5m/s$ depending on the location the devise was held. However, in the collection of the three different airfoils lift values, the wind tunnel was not turned off or changed. And the value being measured was not varying beyond $\pm 1g$ for weight change values of $5g - 250g$. The quality of airflow was a major area of improvement for wind tunnels through their development. G.I Taylor made a remark in the early 1920's to the effect that small scale turbulence would only rarely exist in the atmosphere, but in wind tunnels of the day there was likely to be an abundance of small scale eddies.

Drag is a force that can be measured on an airfoil and the lift to drag ratio can provide some useful information. Originally this experiment was intending to measure the drag force because research and simulations suggested that camber would increase the total lift but decrease the lift to drag ratio. However the apparatus used to hold the airfoil made it difficult to measure drag accurately. The apparatus had a hing at pivot point B which in principle could allow a force to be measured parallel to the air flow direction by having a force gage in contact with the back edge close to pivot point A. However the system is much like an unstable inverted solid arm pendulum. The system is resting counter clockwise from the apex, and for a displacement to be measured in the horizontal direction the weight of the system would have to first be countered. Then as the pendulum swings past its apex, a gravitational torque is applied and a greater force would be measured.

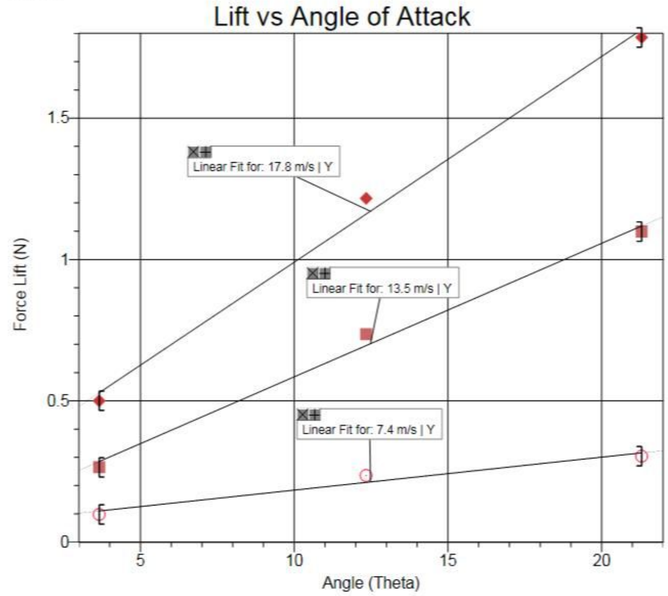
Based on the simulations run on NASA's FoilSim 2, a change of lift to drag relation would only be evident with a change from 0% to 10% camber, and the software used to create the profiles would only allow a maximum of 5% camber. If an airfoil silhouette of 10% camber could have been easily created, then even the rough measurements of drag might have shown interesting data. A more stable apparatus that allowed drag measurements would be invaluable to any future studies.

8. CONCLUSION

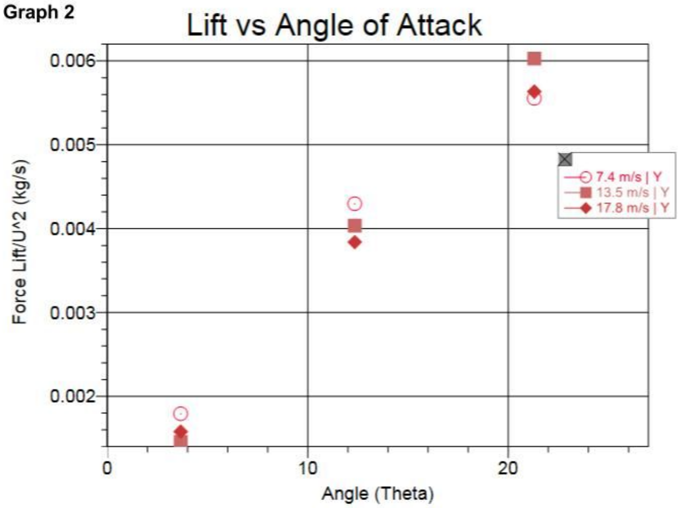
The results obtained in this experiment clearly support three main dependencies of lift, air speed, angle of attack, and circulation dependence on shape. The data in Graph 1 clearly shows three separate lifts for different speeds of air flow, but after dividing by U^2 it is evident that each air speed lift at a set angle of attack is similar. Graph 3 demonstrates the linear relationship at small angles between lift and angle of attack up to the stall point, and shows the drop off of lift after the stall point. However one would hardly consider angles of 15-30 degrees as 'small angles, but the linear relationship maintains well up till stall at 40 degrees. A cambered airfoil provides more lift at all angles of attack compared to the un-cambered version, and an airfoil shape provides better lift than a thick plate at angles greater then 15 degrees.

Graphs

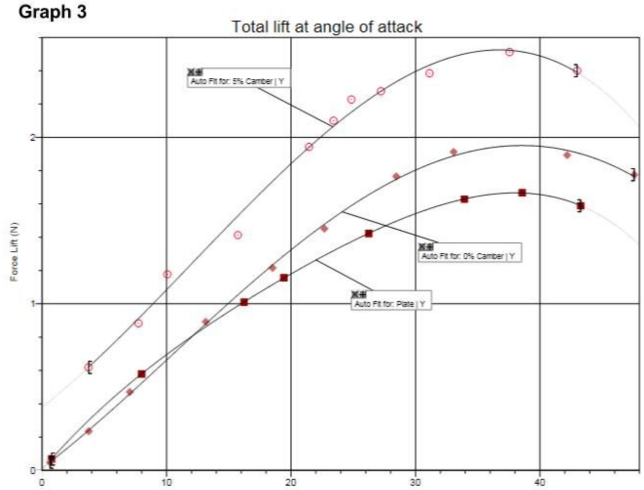
Graph 1



Graph 2



Graph 3



Figures

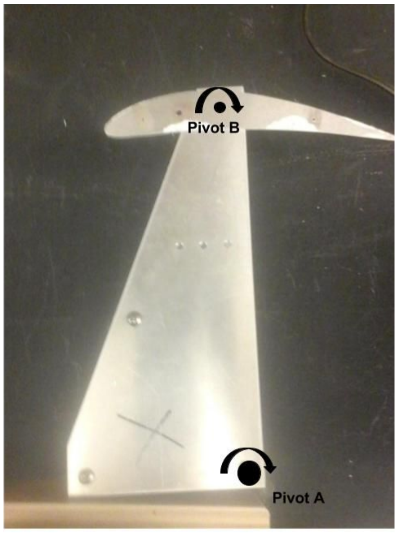


Figure 1

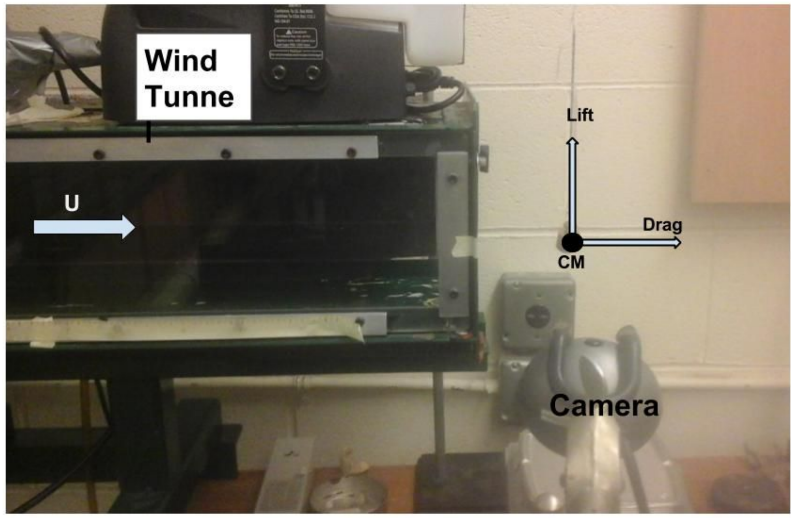


Figure 2

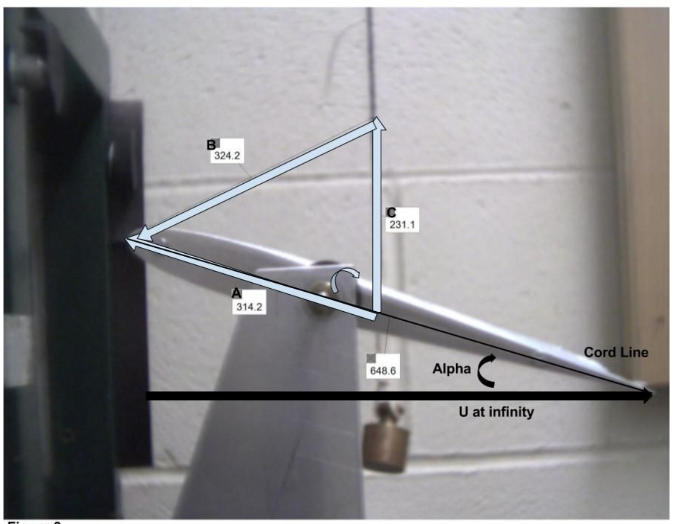


Figure 3

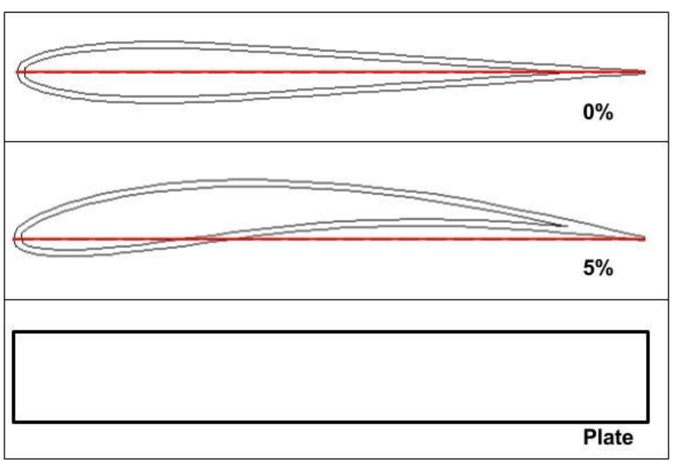
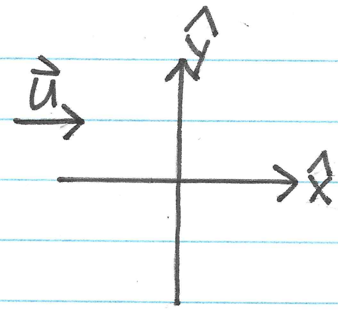


Figure 4

Drawings

1)



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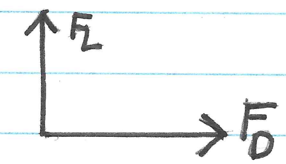
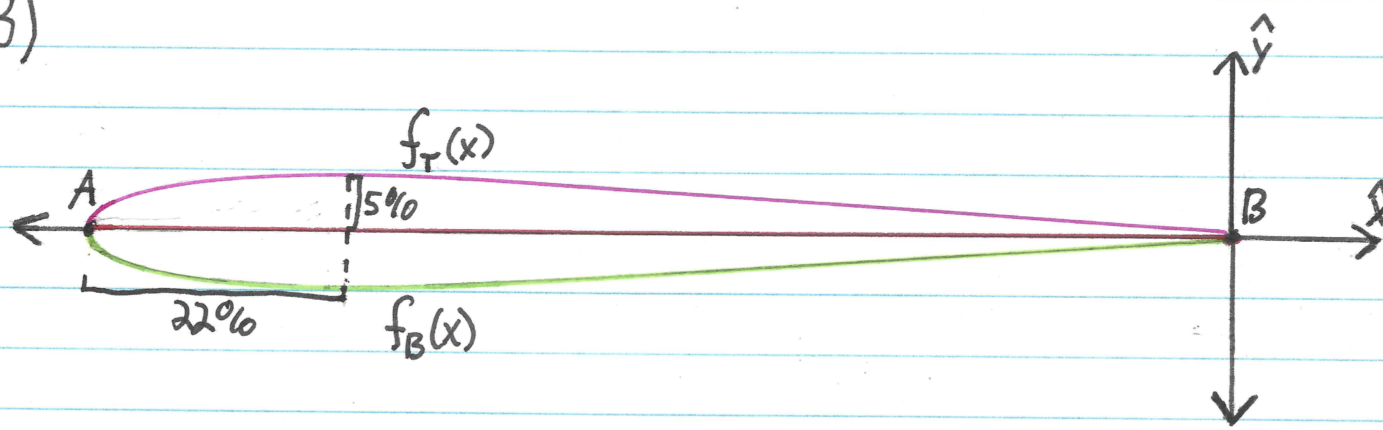
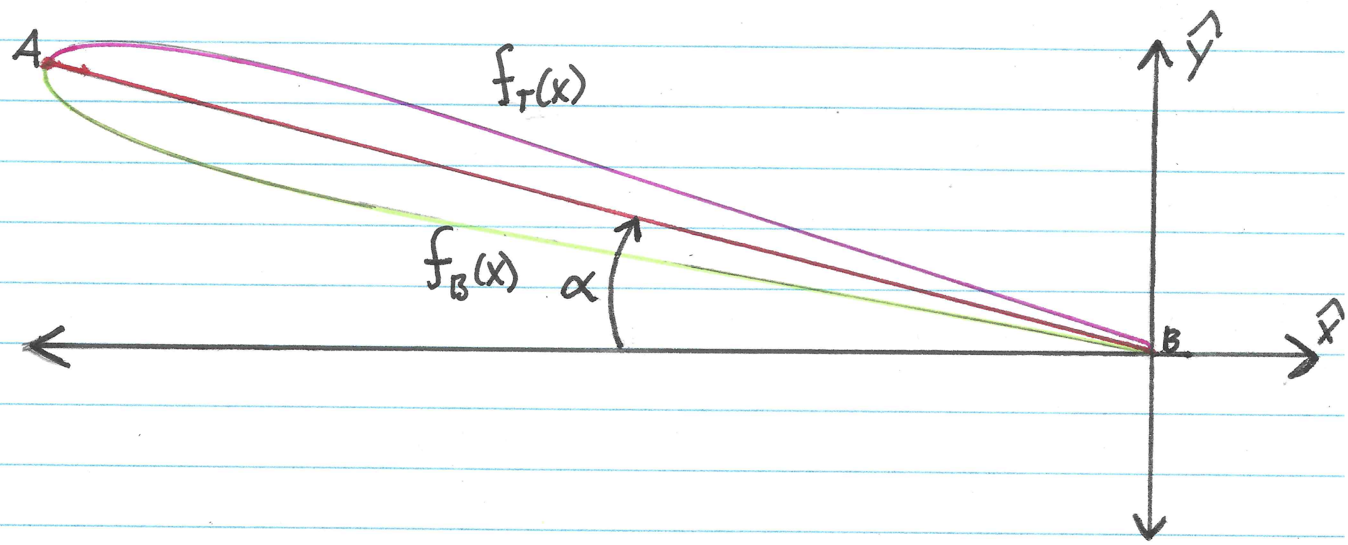


3)



4)



5)