Aerodynamics of Kites

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Abstract

For this lab, the original idea was to figure out how and why a kite flies. From there it was decided that lift, drag and moments would also be calculated and compared among two different designs of kites. One kite was a smaller more diamond shaped kite, and the other was a larger delta shaped kite. The kites were taken to the Boeing wind tunnel to be tested. The most difficult part of gathering the experimental data was deciding how long and where the strings should be. When the strings weren't aligned correctly, the kites would spin out of control and it was impossible to collect data. The optimal position of kite strings proved to be when the strings were separated about a foot and a half, and when the kite was close enough to the wing pedestal so that it could rest on it before takeoff. This must be close to the point where the center of pressure and the center of mass were aligned, causing no net moment on the kite. Once the strings were in optimal position, the kites were tested at different speeds. The LabVIEW program was used to record the flow velocity, drag, and lift on the kite, and pictures were taken when the kite was in equilibrium. This data had to be taken in the first part of the flight, otherwise the kites would start to oscillate and the data was skewed.

With the data that was found, the coefficients of lift and drag were calculated. Drag polars were used to compare the different tunnel speeds and configurations. In addition, using four different angles of attack corresponding to steady flight, the coefficients of lift and drag were plotted against the angle of attack. The angle of attack was measured using trigonometry and the pictures taken during the lab. The first value of velocity in which the coefficient of lift read positive was recorded for each trial, and a graph was made to show the average take-off velocity for each kite.

After the experimental portion of the lab was performed, the theoretical data was found using equations found on NASA's website. Equations for lift and drag coefficients were similar to those used for airfoils, with slight variations. In comparing the experimental data to the theoretical data, the C_L vs. angle of attack curves differed greatly. The experimental graph showed an opposite trend when compared to the theoretical graph. A possible explanation is that, due to the flexible body of the kite and the small flying space, vortices being shed off the wings may have interacted with the air on top of the kite, which in turn skewed the data recorded by the program. As for

the C_D vs. angle of attack curve, a similar trend was found between theoretical and experimental, although there may have been some outliers.

Possible error in this lab could have occurred because the kite is not a full rigid body. With a flexible body, the kite would not perform exactly as expected. Another possible source of error is the vortex interruption experienced on the top of the kite. Finally, the modeler used to get theoretical data from NASA was not fit for the kites used. Instead, an approximate planform shape was used for each kite.

1. Objective

The first objective of the lab was to measure the lift and drag imparted on a kite at different velocities. From these values for lift and drag, the coefficients of lift and drag could be calculated. Another objective of the lab was to determine the center of pressure for the kite at a given angle of attack. The center of pressure could be calculated using photographs of the kite and knowing where the forces of lift and drag act on the kite. Moreover, another objective of the lab was to measure the takeoff speed of the kite. This would give information on how fast the kite would need to be going so that it could produce enough lift to takeoff. The last objective of this lab was to measure the velocity at which the kite will become unstable. This velocity could then be compared to the recommended flying conditions for the kite from the manufacturer. All three of these objectives will help to understand the overall flight properties of the kite and will give a better understanding of aerodynamics. Analyzing pictures that were taken while the kite was in flight will also help strengthen the perception of kite aerodynamics.

1.1 Procedure

1) Log onto LABVIEW and run the Lift, Drag and calibrating programs.
2) Remove any objects or airfoils in the wind tunnel.
3) Calibrate the lift and drag for the wind tunnel
    a. Run the calibration program so that initial values are known.
    b. Place known weights to the balance plate which is found directly below the main chamber of the wind tunnel.
    c. Record values in LABVIEW.
    d. Remove weights from balance plate.
    e. Place known weights on drag wheel which is found toward the back and below the main chamber of the wind tunnel.
    f. Record values in LABVIEW.
    g. Remove weights from drag wheel.

For calibration curves please refer to the appendix.

4) Install the small kite in the wind tunnel. Make sure that the kite is secure to the base with the strings about a foot and a half apart. Also check that kite strings are long enough for the kite to fly freely, but short enough so that the kite will be stable. The kite should be able to rest on the wing pedestal so it has an initial angle of attack.

5) Use the LABVIEW program to zero out lift and drag calculator before each run.

6) Turn on the wind tunnel and observe the flight of the kite.

7) Use LABVIEW to take lift and drag readings during flight.

8) Take pictures of kite during stable flight to observe the angles of the flight.

9) Reset kite to its original position on wing pedestal.

10) Continue running these steps at varying speed from 0 m/s to 15 m/s.

11) Repeat this same process for the larger kite.

NOTE: Due to the unstable nature of kites and the small amount of space that they have to fly in the wind tunnel, make sure that lift and drag readings and pictures are taken in the first part of the flight. After this time oscillations will occur and cause large errors in data.

2. Results and Discussion

Up to this point in aerodynamics lab, the focus has been on wings or other small objects and the effect that wind tunnels or supersonic nozzles have on them. In this lab, a kite presented a very simple case on how a complete aircraft, rather than just parts of it, would behave.

2.1 How Kites Fly

Kites are most commonly created with lightweight material covering a flexible frame. The lightweight material helps to minimize weight, which makes it easier for the kite to create the necessary lift to fly. The flexible frame lets the kite bend to the optimal shape for flying. An unbending kite would more resemble a flat plate than an airfoil. With the curved airfoil shape, the kite is much more able to produce lift. The angles of the strings also play a very important role in deciding how a kite flies. The strings decide how the wind will strike the kite, and what its angle of attack will be.

To see how a kite flies, one can first start by looking at a simple free body diagram of a kite in stable flight when tethered to a string. This is shown in the figure below which was made on a CAD program.
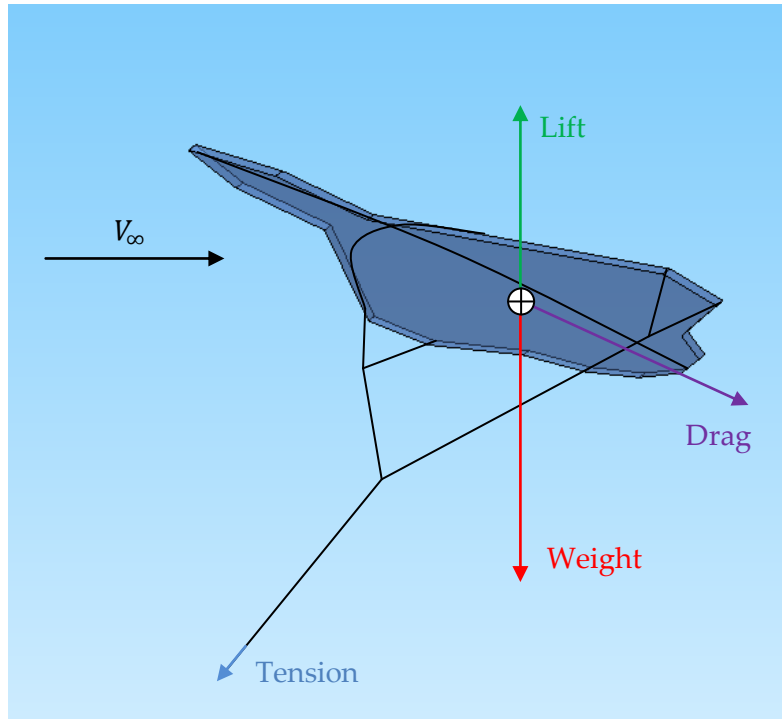
Figure 1: The Forces on a Kite

The forces that act on the kite are lift, drag, and gravity. In order to fly, a kite needs a steady stream of flowing air. This wind, when incident on the frontal surface of the kite flows around the kite, thereby producing lift. There is hence a stagnation point on the frontal surface of the kite, where the pressure is a maximum. The wind also causes a resistive force on the kite, which is basically the drag force, and it is a combination of these forces that keeps the kite in the air. The point of maximum pressure is also the point through which these forces act through, and it is thus known as the center of pressure. Not surprisingly, this is the point where the string is tied and it is commonly known as the tow point. The overall forces on the kite are balanced by the force of the tension along the string of the kite.

2.2 Differing Designs of Kites

There are many different shapes of kites that produce differing results. Some kites are designed to easily lift off the ground, where others are made for stunts. In this lab, a diamond and a delta kite were used. The smaller diamond shaped kite is meant for more stable, slower speed flight. It could do some stunts, but it is not extensively designed for tricks. The larger delta kite is made for faster wind speeds and extensive aerobatics. This suggests that this kite should be inherently less stable and more difficult to control. Another thing that adds onto this control issue is that both of these designs also had two strings. In trained hands, this could mean that there is much more room for control, but in a wind tunnel, this could mean that lack of stability happens quickly. That coupled with the fact that the kites had very little space to freely move means that after a short period of time, the kites should not want to fly steadily in the wind tunnel.

Figure 2: Kite Designs used in this Lab

Above are the two kite designs used in this lab found using Google images. The picture on the left shows the smaller more diamond shaped kite, and the picture on the right shows the larger delta shaped kite. In the next few sections the experimental results from these two types of kites will be discussed.

2.3 Stability of a Kite

For any given object to stay in flight, whether it is a kite, a plane, or a bird, it must remain stable. Stability of any object is very hard to analyze, given the complexity of the flow around the object. However, stability can be summed up in one sentence: the sum of the moments about the center of mass should be equal to zero. The point on the airfoil or kite where the total sum of all the pressure fields acts is the center of pressure. One important characteristic of the center of pressure is that the sum of the moments at that point is zero. This is very important in determining the stability of the kite while it is flying.

When the kite is flying at its equilibrium position, the center of pressure and the center of mass are at the same point on the kite. If the center of pressure of the kite is ahead of the center of mass of the kite, there will be a net moment on the kite. This net moment about the center of mass will cause the kite to pitch up or down depending on the direction of the moment. This is very bad for the stability of the kite, because as the kite starts to pitch away from its equilibrium position, the flow over it will become more unpredictable and the kite will stop producing lift. The kite will immediately become unstable and will follow an unpredictable path. This will eventually lead to the kite losing all lift and falling to the ground.

To help increase the overall stability of the kite while it was flying at high velocities, it was necessary to move the handles farther apart. Moving the handles farther apart from each other would allow the kite to counteract small changes in stability due to yawing and side to side motion. Since the strings were farther apart, they could exert a larger twisting moment on the kite when it was trying to yaw away from the equilibrium. Since the kite was not positioned perfectly relative to the free stream, there was a small moment on the kite that would make it yaw in either direction. Having the handles farther apart from each other made it harder for the kite to yaw in either direction, and therefore made the kite more stable.

2.4 Vortices and Their Effect on Kites

Vortices are formed due to the edges of a wing or aircraft and the tendency of an uneven pressure to try and redistribute itself. In this lab a tricky situation is presented. Rather than the rigid airfoils considered in the previous labs, this lab has an aircraft that will greatly bend and reshape to the forces acting upon it. This coupled with the small space that the kite has to move in the wind tunnel creates great disturbances in the flight pattern of the kite. These disturbances are oscillations up and down, left and right, or both and continue to get more vigorous as time goes on. Eventually the oscillations become too much for the kite and this causes the kite to crash or become tangled in the wind tunnel. This is the reason why it was so important to gather data in the first part of the flight so that the more realistic data could be presented.
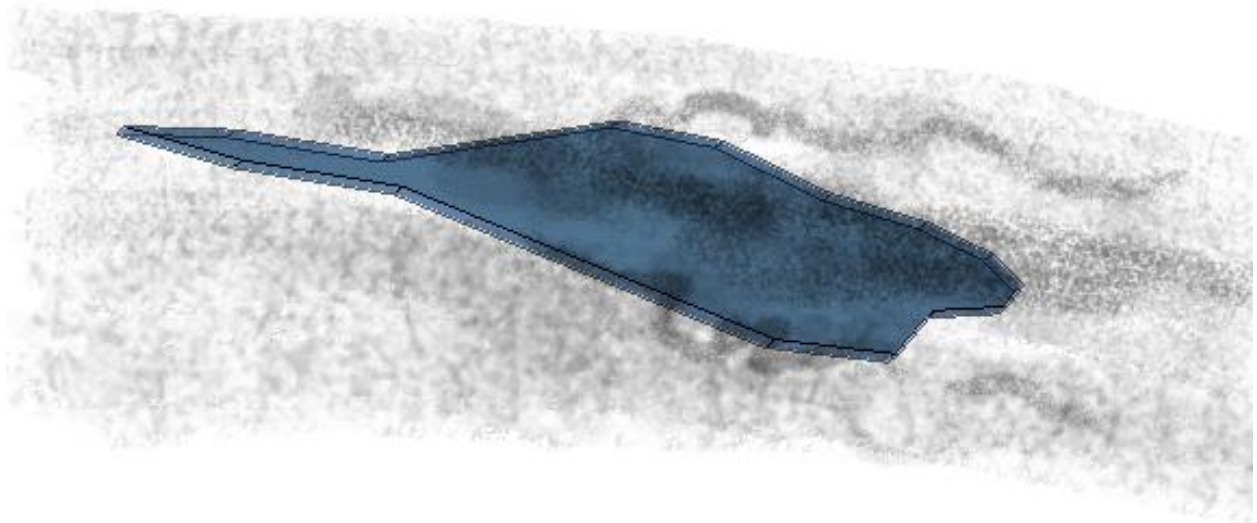
Figure 3.1: Simulated Smoke Analysis with Kite

Figure 3.2 below shows the large kite in flight in the wind tunnel. This kite was extremely difficult to control due to its large size and its unstable nature. The vortices affected this kite much more than it did the smaller kite. At higher speeds the large kite had to be stabilized in the air then let go of in order to get accurate data as shown in the figure.

Figure 3.2: Large kite in the Wind Tunnel

2.5 Theoretical Lift and Drag Data

Calculating the theoretical values of the coefficients of lift and drag was important to test the results that were produced in the lab. The theoretical value for the lift coefficient of a kite is given by the following equation:

$$C_l = \frac{C_{l0}}{1 + \frac{C_{l0}}{\pi * AR}}$$
    Equation 1

C_l = Coefficient of Lift

C_{l0} = Coefficient of Lift for a flat plate = $2 * \pi * aoa$ (angle of attack in radians)

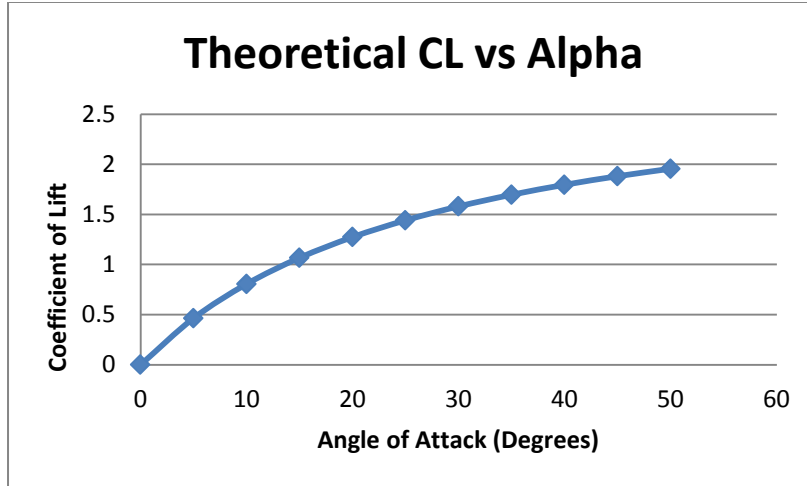AR = aspect ratio of the kite (wingspan^2/surface area)

Figure 4: Theoretical coefficient of lift versus angle of attack

C_{l0} is the lift coefficient for a flat plate at a given angle of attack. Since a kite can be mostly modeled by several flat plates at different angles of attack, this value is just a starting value for the coefficient of lift for the entire kite. Furthermore, to calculate the coefficient of drag for the kite, the following equation was used:

$$C_d = C_{d0} + \frac{C_l^2}{.7 * \pi * AR}$$ Equation 2

C_d = Coefficient of Drag

C_{d0} = Form Drag for the kite = $1.28 * \sin(aoa)$

C_l = Coefficient of lift

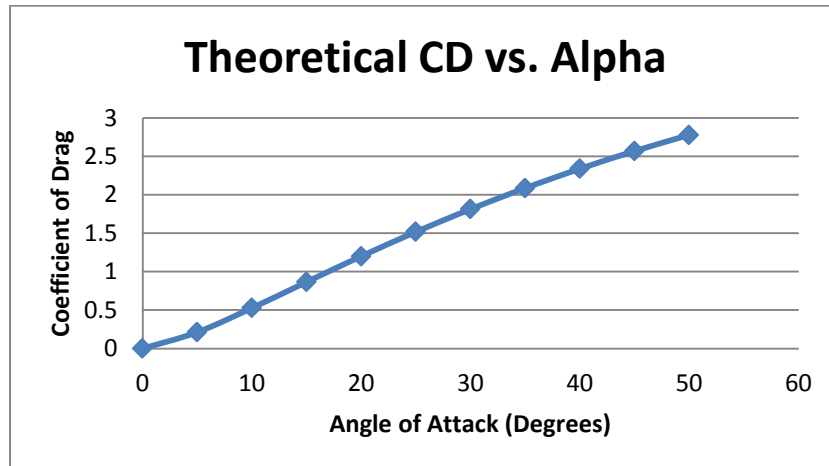AR = aspect ratio of the kite (wingspan^2/surface area)
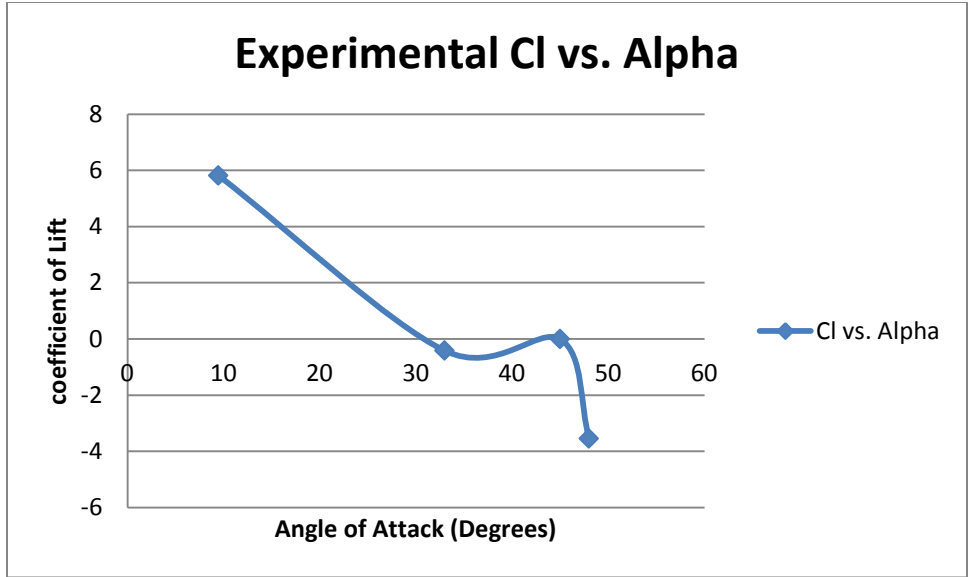

Figure 5: Theoretical coefficient of lift versus angle of attack

2.6 Experimental Lift and Drag Data

The data that was calculated in the lab was compared to the theoretical data for the given kite to see how accurate the results obtained in the lab were. There were three main graphs for the kite that were compared to the theoretical values as a way to measure the aerodynamic effects on the kite. These graphs include the drag polar, the coefficient of lift versus angle of attack, and the coefficient of drag versus angle of attack.

From common knowledge of airfoils, it is obvious that the coefficient of lift increase as the angle of attack is also increased. This was the same trend that was seen for the theoretical results for the kite in the coefficient of lift versus angle of attack graph. It shows that when you increase the angle of attack of the kite, the coefficient of lift will also increase: the same results that were obtained for airfoils. However, the actual data that was recorded in the lab does not agree with the theoretical data for the given kite. The data collected in the lab shows that when the angle of attack is increased, the coefficient of lift will decrease. This goes against the intuition of the theoretical results. This is due to the fact that the theoretical results do not include vortices that are formed around the kite, that actually push the kite downward and reduce the coefficient of lift. These vortices will increase exponentially as the angle of attack is increased which is why the slope of the coefficient of lift versus angle of attack graph is negative. These vortices had a significant impact on the overall aerodynamics of the kite and will also provide a large contribution to the coefficient of drag.

Experimental Cl vs. Alpha

Figure 6: Experimental coefficient of lift versus angle of attack

The coefficient of drag for a given body is an important aerodynamic quantity used to show the overall effectiveness of an object in flight. However, just like the coefficient of lift, the coefficient of drag also increases as angle of attack is increased. The theoretical values for coefficient of drag were compared to the results that were measured in the lab, and the results were inconclusive. Even though both graphs have a positive slope and increase with angle of attack, there is a significant decrease in drag coefficient at 45 degree angle of attack. The overall shape of the coefficient of drag versus angle of attack does not agree with the theoretical graph, but is more accurate than the coefficient of lift graph. This could be partly due to the vortices that were formed around the kite or an incorrect value measured by the gauges. No matter what the case, the theoretical values of lift and drag coefficients are different for a kite than the actual results obtained in the lab.
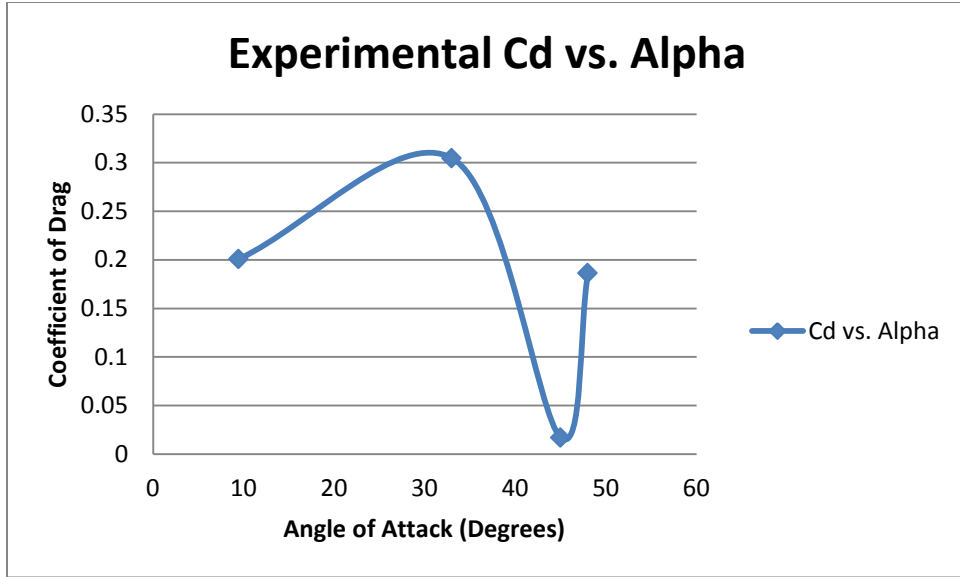
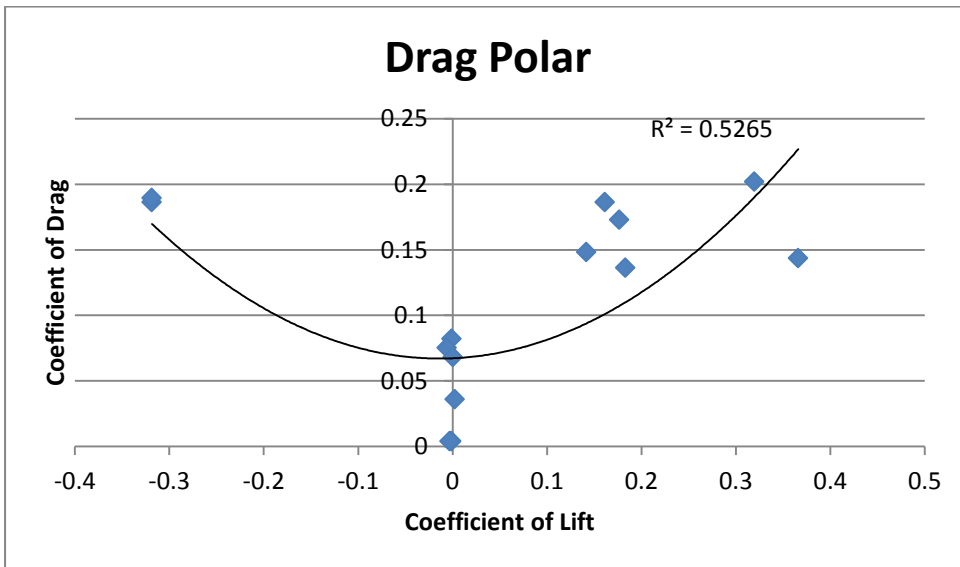**Figure 7: Experimental coefficient of drag versus angle of attack**

Figure 8: Experimental Drag Polar

2.7 Pictures for Angles and Moments on the Small Kite

Figure 9 shows the kite flying at an angle of attack of 8 degrees. The angle was found by superimposing an image of the protractor on top of the figure and using it to

find the angle of the chord line. In this configuration, the kite was in stable flight but very unstable. After about twenty seconds of flight, the kite began to wobble and then flip around, getting caught on the bracket. Any perturbation would cause it to become unstable, including increasing the tunnel speed. As a result, this picture was taken when the wind tunnel was at the critical speed necessary to maintain level flight.

Figure 9: Mostly stable flight at 18 degree angle

Figure 10 shows the kite at an angle of 47 degrees. This configuration was much more stable than when the kite was flying at 8 degrees. The tunnel speed was able to be increased with the kite remaining in stable flight.

Figure 10: Stable flight at 47 degree angle

2.8 Calculations of Angles and Moments on the Small Kite

Below are the two free body diagrams of the kite. One is the kite with a large angle of attack and the other is the kite with a small angle of attack. The angle of attacks were changed by changing the length of the strings.
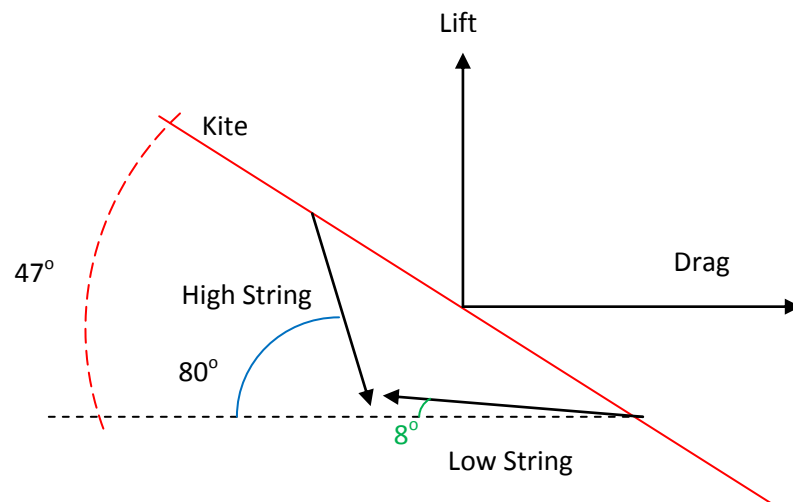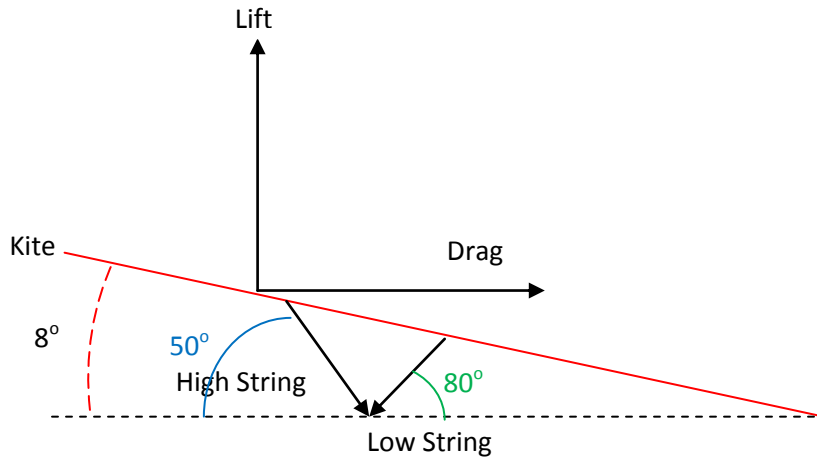

**Figure 11: Free Body Diagram of Low Speed Flight (not to scale)**

Figure 12: Free Body Diagram of High Speed Flight (Not to Scale)

Using these free body diagrams, an analysis of the forces can help find the moment about the kite. Wherever the moment is zero is where the center of pressure of the moment will be for the kite. A couple of assumptions were made to simplify the analysis of the data. The first assumption being that the kite is taken to be 2 dimensional. This means that the kite is assumed to be perfectly symmetrical and that the strings on both sides of the kite perfectly split the forces of the lift and drag. This is a fair assumption since the angle of attack only varies with the pitch, so no data involving roll or yaw is necessary to find the varying center of pressure due to angle of attack.

The second assumption is that the lift and drag forces act on the center of pressure, so the moment of lift and drag are zero at all times. Therefore, wherever the moment is being evaluated on the kite, only the forces of the two strings create a moment. When the moment of the two strings equals zero, this will be deemed the true center of pressure. In reality, the point where the lift and drag acts is constantly changing with the kite, since the kite does not hold a rigid shape when it flies. By the kite flapping and flexing against the vortices created, it causes a moment from the lift and drag that can cause the kite to become unstable.

The last assumption is that the center of mass is at the half chord point. This is done by summing the center of masses of the three components that make up the kite.

The kite has two plastic rods that are used to make the kite structurally sound. The first goes the whole length of the kite and the other goes across the wing span of the kite. The rods are made of the same material. Assuming the density is uniform throughout the rods, it can be concluded that the center of mass is at the halfway point of both rod's length. The kite's center of mass is more difficult to assume since it is not a rigid body and not a simple geometric shape. However it is also safe to assume that the kite is very light compared to the two rods, so the rods will have more effect on the center of mass. By looking at the kite, it is fair to see that more material is in the back half of the kite as opposed to the front end. More material on the back half of the kite means the kite will have a center of mass further back along the chord. Below is a diagram to help visualize the center of mass.
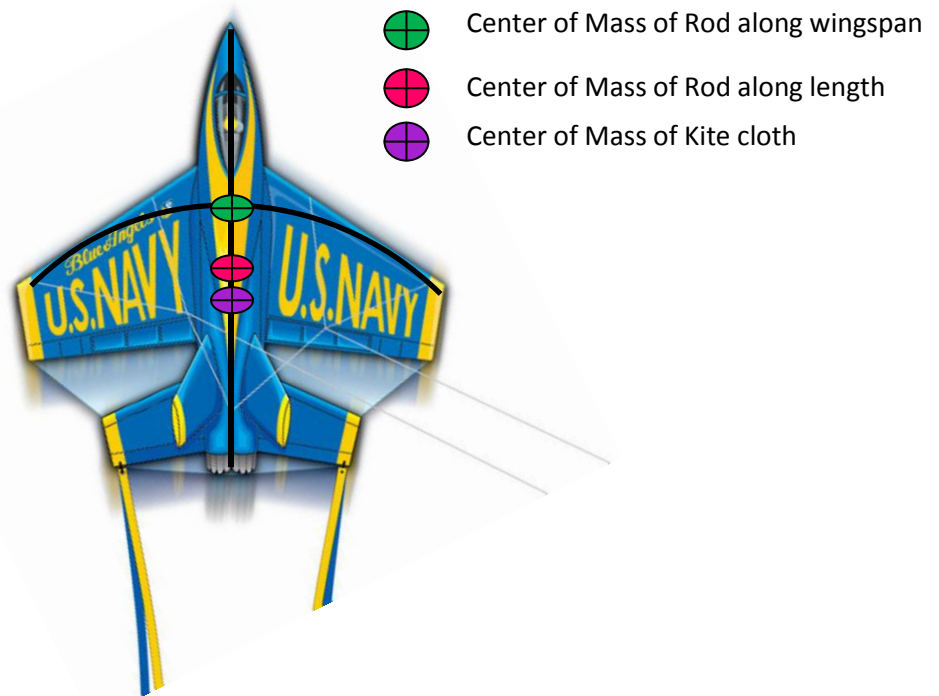
Figure 13: Center of Mass of Kite Components.

By summing these three centers of masses together, it is safe to say that the center of mass will be approximately by the half way point along the chord for the kite. Although it is difficult to actually measure the center of mass for this kite, by approximating the center of mass it will help give information where the center of pressure should be so that the kite is most stable. The goal is to have the center of

pressure and the center of mass as close together as possible in order for the kite to be most stable during flight. The center of mass and center of pressure need to be close together because it helps reduce the pitching moment and therefore increases the stability of the craft.

Using these assumptions the forces in the strings can now be found. Using the FBD's (free body diagram), two equations were found to find the force in both strings for both kite angles of attack.

$$L = Rsin\emptyset_R + Hsin\emptyset_H \qquad \text{Equation 3}$$

$$D = Rcos\emptyset_R + Hcos\emptyset_H \qquad \text{Equation 4}$$

where D is the drag force, L is the lift force, R is the force in the lower string, H is the force in the higher string, $\emptyset_R$ is the angle of the lower string and $\emptyset_H$ is the angle of the higher string. Since L and D were both found during the experiment, R and H can be calculated. Now that R and H are known, the moment of the two forces can be found.

Since the kite is at an angle of attack, the forces of R and H need to be split up in the normal and axial force.

$$R_{axial} = Rcos\emptyset_R \qquad \text{Equation 5}$$

$$R_{normal} = Rsin\emptyset_R \qquad \text{Equation 6}$$

$$H_{axial} = Hcos\emptyset_H \qquad \text{Equation 7}$$

$$H_{normal} = Hsin\emptyset_H \qquad \text{Equation 8}$$

Also the kite's chord needs to be broken up into components since it is at an angle of attack relative to the ground.

$$l_{r,x} = l_r cos\alpha \qquad \text{Equation 9}$$

$$l_{r,y} = l_r sin\alpha \qquad \text{Equation 10}$$

$$l_{h,x} = l_h cos\alpha \qquad \text{Equation 11}$$

$$l_{h,y} = l_h sin\alpha \quad \text{Equation 12}$$

where l_r is the length from the leading edge to the low string, l_h is the length from the leading edge to the high string, α is the angle of attack and x and y denotes the broken up components into the inertial frame.

Now the moment can be taken. The moment will be taken at the leading edge, quarter chord and half chord.

$$M_{LE} = l_{r,x} * R_{normal} + l_{r,y} * R_{axial} + l_{h,x} * H_{normal} + l_{h,y} * H_{axial} \quad \text{Equation 13}$$

$$M_{c/4} = (l_{r,x} - c/4) * R_{normal} + (l_{r,y} - c/4) * R_{axial} + (l_{h,x} - c/4) * H_{normal} + (l_{h,y} - c/4) * H_{axial} \quad \text{Equation 14}$$

$$M_{c/2} = (l_{r,x} - c/2) * R_{normal} + (l_{r,y} - c/2) * R_{axial} + (l_{h,x} - c/2) * H_{normal} + (l_{h,y} - c/2) * H_{axial} \quad \text{Equation 15}$$

Where M_{LE} is the moment at the leading edge, $M_{c/4}$ is the moment at the quarter chord, $M_{c/2}$ is the moment at the half chord, and c/4 is the length from the leading edge to the quarter chord, and c/2 is the length from the leading edge to the half way point. The moment and forces found were:

Angle of Attack = 47 degrees		Angle of Attack = 8 degrees	
Speed	3.005 m/s	Speed	4.522 m/s
Force of Low String	1.014 N	Force of Low String	-0.083 N
Force of High String	1.132N	Force of High String	0.100 N
Moment(LE)	0.663 N-m	Moment(LE)	0.021 N-m
Moment(c/4)	0.321 N-m	Moment(c/4)	0.005 N-m
Moment(c/2)	-0.047N-m	Moment(c/2)	-0.021 N-m

Table 1: Force and Moment Data

Moments on the Chord
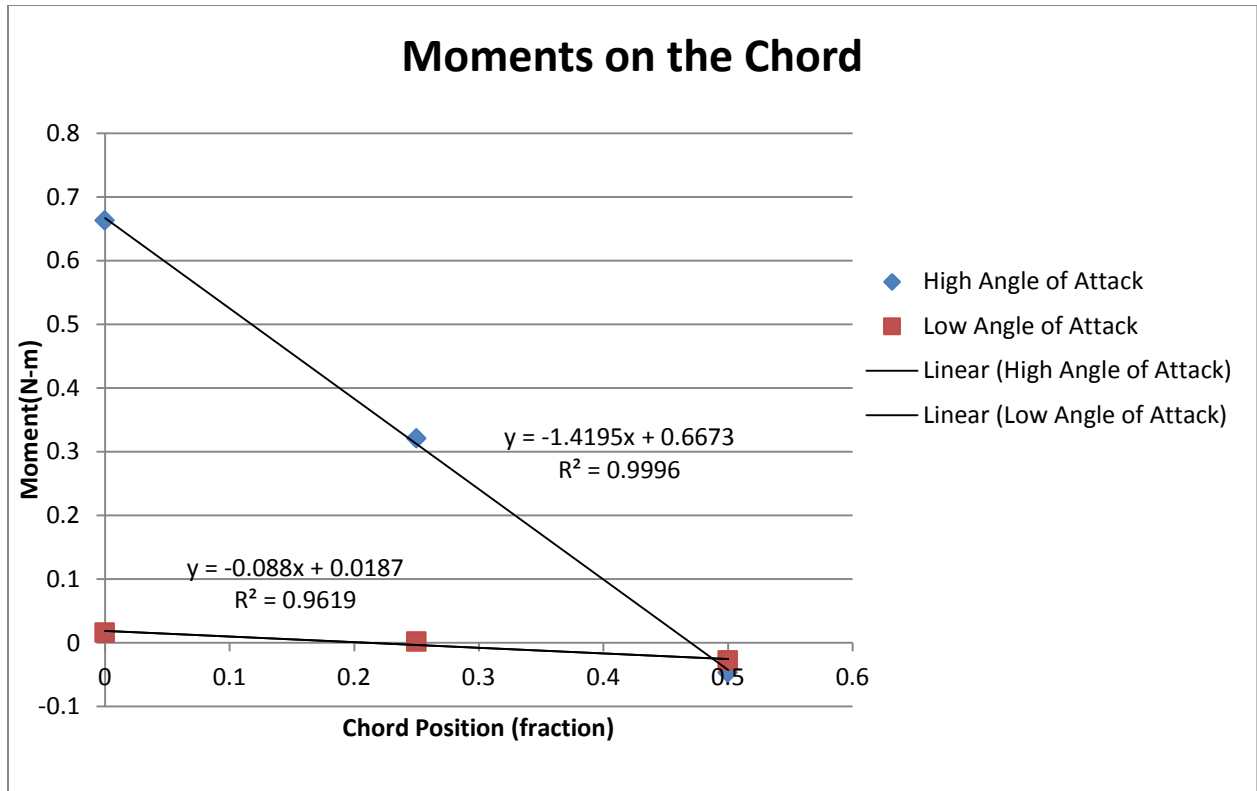
Figure 14: Moments on the Chord

For both angles of attack, the moment decreases as one goes down the chord to the half way point. Also, both of the moments equal zero somewhere between the quarter chord and the half chord points. This is known because the moment is positive at the quarter chord and negative at the half chord. The differences between the high angle of attack and the low angle of attack are the differences between the moment values. The high angle of attack has a very large moment because the lift and drag is greater on the kite. The kite at a low angle of attack has a very small angle of attack. This is because the kite is more streamline to the flow of the wind tunnel, therefore reducing drag and lift.

Using the linear equations displayed on figure 13, one can find where the moment equals zero or the center of pressure. The center of pressure for the low angle of attack occurs at 21.25% of the chord, while the center of pressure for the high angle of attack occurs at 47% of the chord. Therefore the higher angle of attack will result in a more stable kite, because the center of pressure is very close to the assumed center of mass near 50% of the chord point. These results make sense because a kite usually flies at a very high angle of attack when in the sky.   If a kite in the sky tends to fly at a

higher angle of attack, the kite must be more stable at higher angles of attack. This is also true while performing the lab. The kite would rise to an angle of attack around 47 degrees on its own and stay stable for a good amount of time. In order to make the kite stable at the 8 degree angle of attack, lab group members had to move the kite there in order for the kite to be stable.

2.9 Starting Velocity

One of the objectives of the lab was to analyze the starting velocity for the kite(s), which is basically the velocity at which the kite just gets airborne. Any velocity, smaller than the starting velocity, will not cause sufficient lift on the kite to make it airborne. As expected, from Figure 14 one can see that the larger kite has a higher starting velocity. So, although the larger kite is more stable in flight, it is harder to get the kite airborne initially. On average, around 0.75 m/s freestream velocity is required to make the small kite airborne, while 3.27 m/s is the average starting velocity for the larger kite.
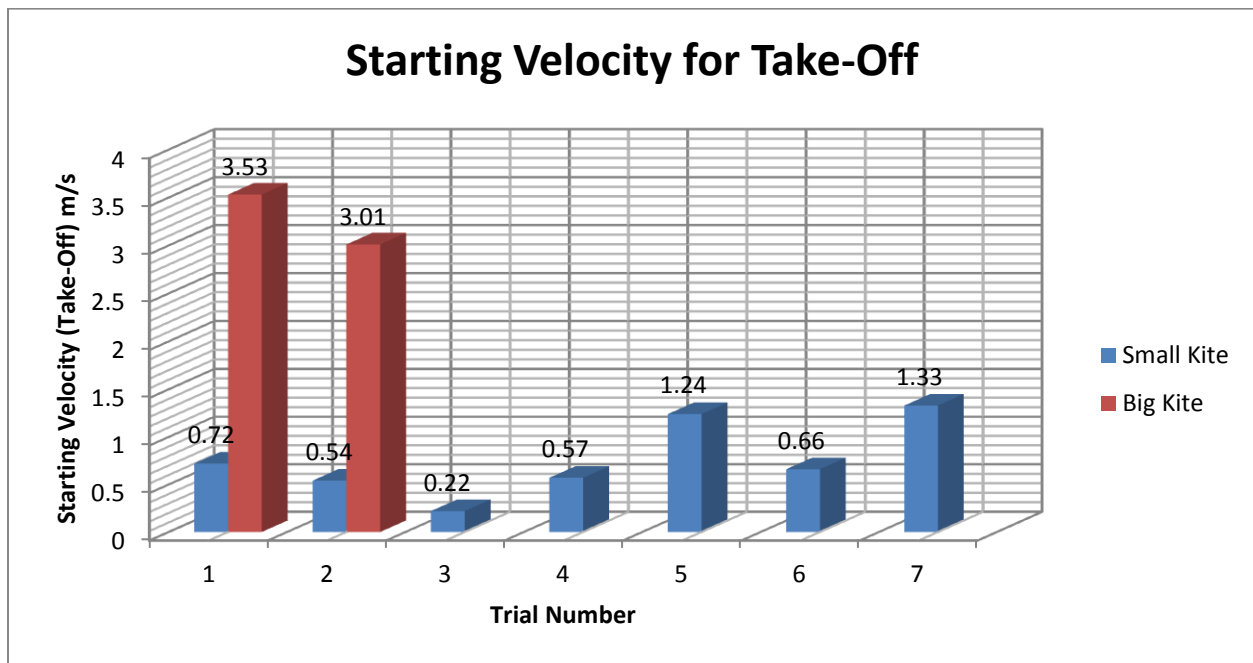

Figure 15: Starting velocity vs. Trial

3. Error Analysis

3.1 Sources of Error

The first error to think about from a modeling perspective is that the kite is not a rigid body. First, the frame of the kite is able to be deformed, as evident by Figure 15. Secondly, the skin of the kite is flexible, constrained by the frame. Obviously, with both frame and skin deforming with respect to each other, this introduces error in the calculations.

Figure 16: Demonstration of how the kite is flexible

Another error came with the vortices produced from the kite inside the wind tunnel. Again, with the flexible structure and the small testing space, vortices may have interacted with the flow over top of the kite. Additional error could have arisen from the way moments were calculated. The kite was assumed to be perfectly symmetric and the moments were calculated in a two-dimensional manner.

Since the values for theoretical lift and drag were taken off of NASA's Kite Modeler, the small kite had to be approximated as a diamond shape, and the large kite was approximated to be a delta kite. This is a fair approximation, but it introduces some error into the calculations. Other errors could have occurred from human and instrumentation error. For example, changing the string lengths in order to make the

kite fly was done by tying the strings in different places. Since this was done by eye, the point of the strings could vary slightly, partially skewing data.

3.2 Error Calculation

Figure 17 shows the percent error associated with each value of coefficient of lift and drag that was measured in the lab. The data was taken when the kite was in steady flight and was compared to theoretical values calculated on the NASA kite modeling software. It is clear that the data measured in lab was very inconsistent and not accurate. This shows the number of sources of error that were present in the lab and just how hard it is to get accurate data in the lab.
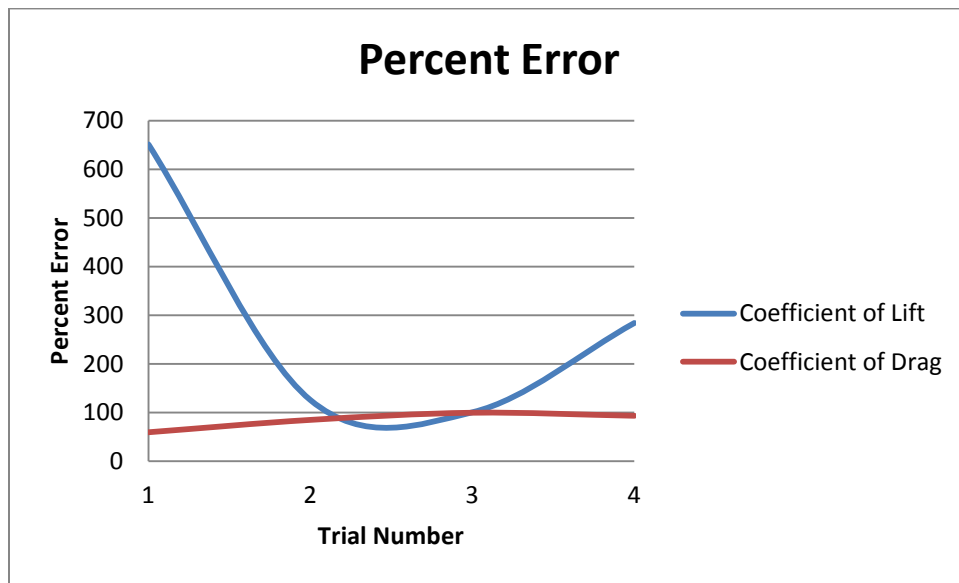

Figure 17: Percent error for each trial

Figures 18 and 19 show the standard deviation of the data that was collected when the kite was in steady level flight for several different trials. Theoretically, the standard deviation should be small compared to the recorded values. However, the standard deviation for both the coefficients of lift and drag are substantial compared to the measured values. This shows how inconsistent the data actually is, and is another possible source of error.
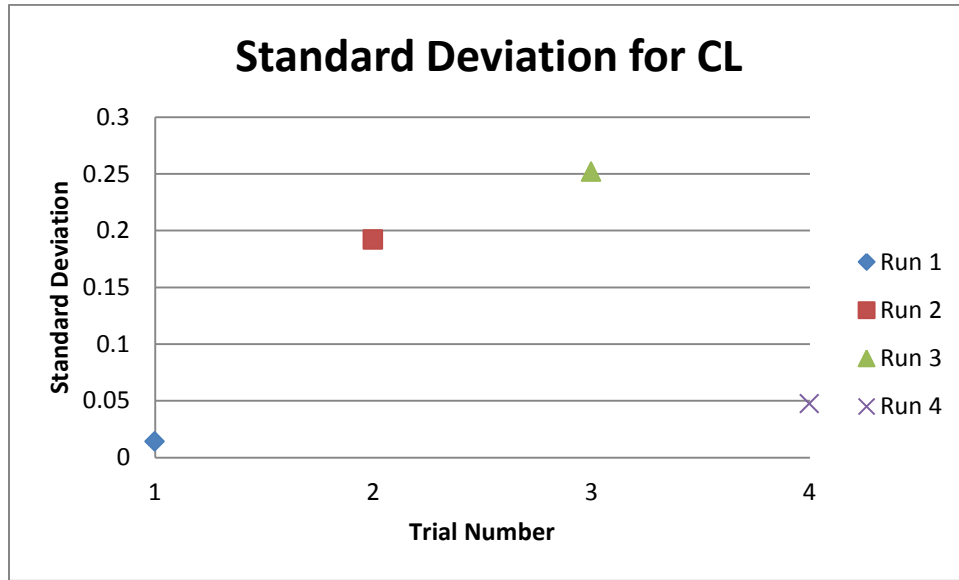

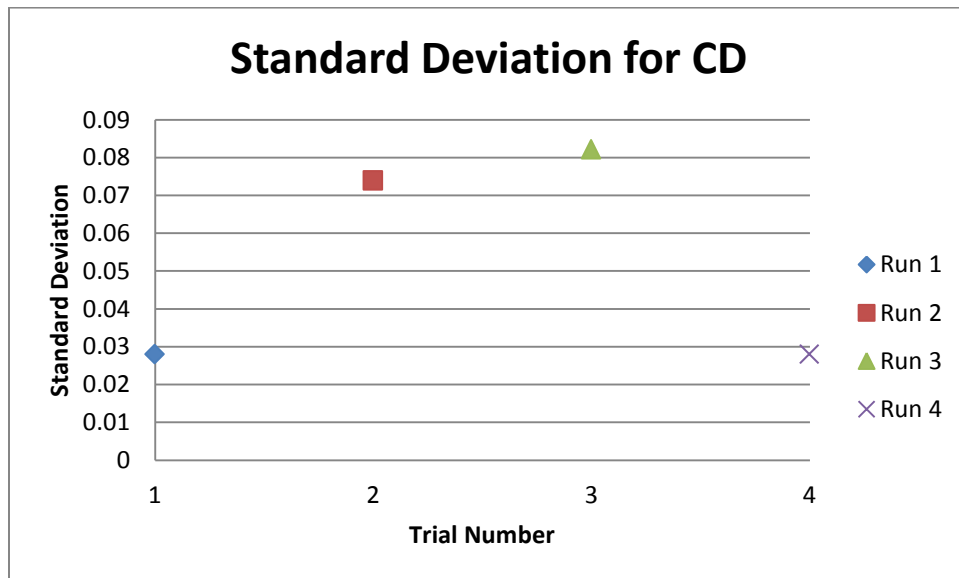**Figure 18: Standard deviation for coefficient of lift**

Figure 19: Standard deviation for coefficient of drag

4. Conclusion

Overall, this lab was a success. All of the three objectives were met. The first objective of the lab was to measure the lift and drag imparted on a kite at different velocities. This objective was accomplished by attaching both the small and large kites to the Boeing tunnel apparatus. Differing velocities were tested for both kites and it showed that the coefficient of lift and drag varied greatly among the experimental and theoretical results. This great difference was probably due to the fact that the kites were in such a small space and the vortices that formed off the kites affected the lift and drag readings.

Another objective of the lab was to determine the center of pressure for the kite at a given angle of attack. For this objective, two pictures of the smaller kite were taken and analyzed. The angles of these kites were measured from the pictures and free body diagrams were created. From these free body diagrams, the moments about the kite were calculated. There were three assumptions made for this: the kite is two dimensional, the lift and drag forces act at the center of pressure and the center of mass is at the half chord point. The conclusion drawn from these calculations were that the high angle of attack has a very large moment due to larger amount of lift and drag and the small angle of attack has a smaller moment. The center of pressure for the low angle of attack was at 21.25% of chord and the 47% for the high angle of attack.

The last objective of the lab was to measure the takeoff speed of the kite. On an average, a 0.75 m/s velocity lifted the small kite and a 3.27 m/s velocity lifted the large kite. This shows that the larger kite has a larger starting velocity. This makes sense due to the fact that the larger kite simply weighs more than the smaller kite.

Other things discussed in this lab included how a kite flies, the differing designs of a kite, and vortices and their effect on kites. A kite flies by the forces of lift, drag, weight and tension from the kite string. There are differing designs of kites that are made for many differing purposes. The two designs of kites that were used in this lab were diamond and delta. The smaller diamond shaped kite was more stable than the larger delta shaped kite. This is because the delta shaped kite was meant for stunts and is therefore slightly less stable. There were also vortices formed off of the kites in this lab. These vortices were caused by the edges of the kite, the fact that the kite bends easily and the fact that kites are designed to catch drafts of wind. The vortices affected the kite so much due to the small space of the wind tunnel. Because of these vortices, the kites after a short period of time would start to oscillate and bounce until they were no longer in flight.

The last topic that was discussed in this lab was the error. These errors included the fact that the kite was not a rigid body and the moments were calculated assuming it was, the vortices that were formed in the wind tunnel, and the diamond and delta shapes for the

theoretical calculations were only approximations. The percent error from the lift and drag were both fairly large. This proved that the data measured in the lab was very inconsistent and that the theoretical data that was collected might not actually be a good approximation of what this lab was trying to accomplish. The standard deviation of the data was also fairly large between trials for both the coefficient of lift and the coefficient of drag. This still shows that the data collected was very inconsistent with itself.

Over the course of the lab, one realizes that setting up the experimentation is non-trivial. Once the experiment has been set up correctly though, getting the kite to fly is not necessarily that difficult. However, one has to get an intuitive understanding of the behavior of the kite as the wind tunnel velocity is increased or decreased and accordingly the string length can be changed to get the desired result of stable flight.

An easier way of getting pitching moment for the kite would have significantly improved the results. The mechanical arm that records the moment value could not be used for this particular lab due to the kind of setup. Running smoke through the wind tunnel would have been interesting as well to observe. The vortex shedding could be analyzed this way as well. If a larger kite is to be used, one would require a larger wind tunnel. Larger kites would produce more lift, and would fly more steadily during the experiment. This would reduce the error significantly. In addition, finding a method of systematically varying the angle of attack would increase the validity of the calculations. Other than that, minor improvements may be made in method of recording data, and taking higher resolution images.
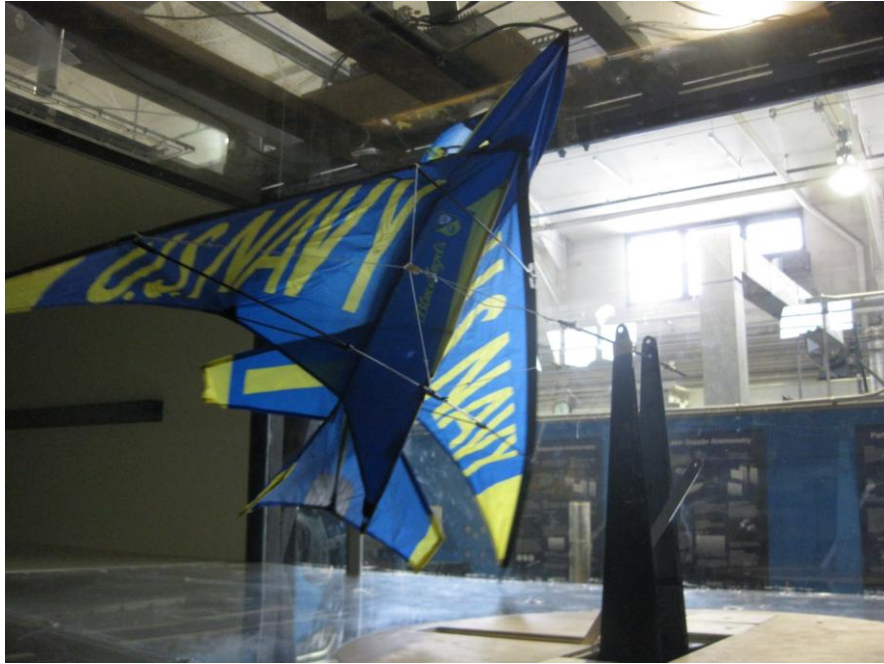
5. Appendix

Figure 20.1: Wind Tunnel Image for Large Kite

Figure 20.2: Wind Tunnel Image for Large Kite

Sample Calculations

Coefficient of Lift

$$C_L = \frac{L}{q_\infty S}$$

$For\ L = 5N, and\ q_\infty = \frac{1}{2} * (1.2) * (0.5)^2, where\ 0.5 = V_\infty\ \&\ S = 2m^2$

$$C_L = \frac{(5)}{(0.15)(2)} = 16$$

Moment and Force Calculations

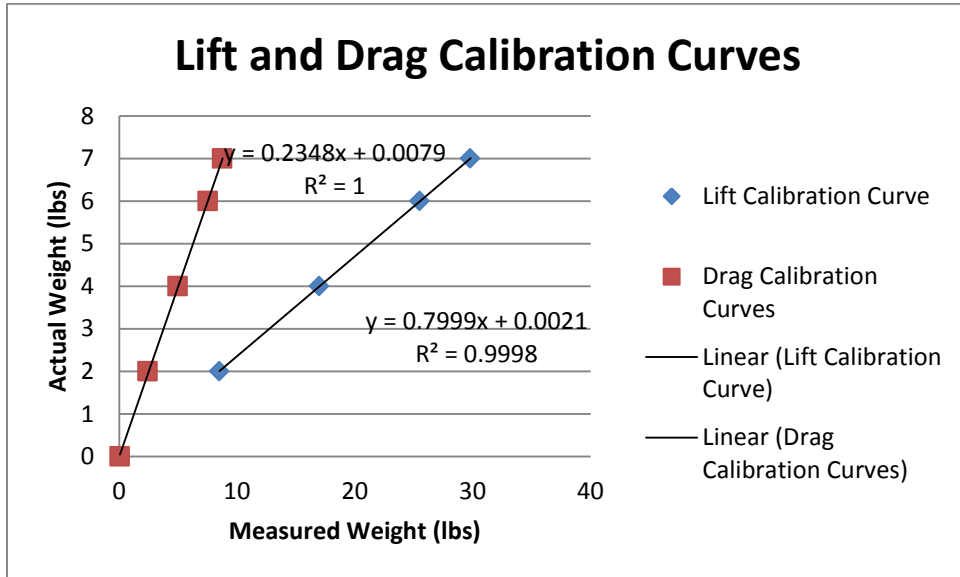$L = Rsin\emptyset_R + Hsin\emptyset_H = 1.257\ N = Rsin(1.396\ rad) + Hsin(0.139\ rad)$

$D = Rcos\emptyset_R + Hcos\emptyset_H = 1.201\ N = Rcos(1.396\ rad) + Hsin(0.139\ rad)$

$R_{axial} = Rcos\emptyset_R$ = 1.014N*cos(1.396 rad) = 0.141 N

$l_{r,x} = l_r cos\alpha = 0.7874N * cos(47\ degrees) = 0.358$N

$M_{LE} = l_{r,x} * R_{normal} + l_{r,y} * R_{axial} + l_{h,x} * H_{normal} + l_{h,y} * H_{axial} = 0.358m * 1.004N + 0.384m *$ .141N + 0.179m * 0.197N + 0.192m * 1.115N = 0.663\ Nm$

Calibration Data

Figure 21: Lift and Drag Calibration Curves

The data recorded from placing multiple weights on the drag and lift plates were graphed in Excel. Then a best fit linear equation was found for the increase in lift and drag as weight was added to the plates. The y-intercept is the amount the lift and drag are off. These values were added onto the experimental values recorded of lift and drag. The experimental value and the calibration value summed together is the value used for computations in this lab.

6. Works Cited

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