The Effect of Wing Sweep, Thickness, and Proportion of Airfoils on Lift

Alexandru Otlacan and Imtiaz Qureshi

Macomb Mathematics Science Technology Center

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This research experiment aimed to determine which factor between wing sweep, thickness, and proportion of airfoils and combination of these factors have the largest effect of lift. The purpose for this goal was to find ways to make planes more efficient. The experiment consisted of airfoils that are commercially accepted on various slow flying aircrafts and then modulated to fit in a Design of Experiment format.

It was hypothesized that the thinnest wings that were not swept back would produce the greatest lift. To test the hypothesis, a wooden dowel drilled into a wooden triangle was created and placed inside of a wind tunnel to hold each pair of designed wings. The way to achieve custom modifications of plane wings was to model and 3D print each wing pair. Each wing pair had a slot where it could slide onto the wooden dowel and into the wind tunnel provided by the Macomb Mathematics Science Technology Center. To conduct the trials, the wings were assigned numbers and then randomized within the format of a Design of Experiment. The wing pair was placed onto the dowel inside the wind tunnel. From there, the wind tunnel would be activated and the wings would rise up the dowel until they became stable. The distance from the bottom of the wing at rest would be measured up to where the bottom of the wings rose was then measured to see how much distance the wings rose.

It was found that wing thickness had the greatest effect on the lift followed by the sweep and then the interaction effect of the two. The best performing wing had low thickness, high proportion, and no sweep as it rose to the max height of 200 mm each time it was tested.

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Introduction

Over the last century, commercial aircraft have come to dominate long distance travel. The key to airline dominance is their efficiency. A single airliner can carry up to hundreds of people on a single trip. On average, a typical airliner is 43% more efficient per passenger than land vehicles (Gross). And they continue to get better as fuel efficiency has increased by 130% in the last four decades (Nast).

All that said, however, the airline industry still faces a massive problem in its near future: climate change. Global warming is becoming an ever increasing catastrophe as years pass by and the global average temperature rises. The airline industry must be able to adjust to these global circumstances in the next few decades. There has already been a movement to make all current vehicles electric including planes. However, electric planes still run into the problem of efficiency as carrying batteries is a lot more difficult than carrying kerosene due to batteries being a lot heavier. Electric planes, for the most part, are still in development and it might take several decades for the mass production of large electric airliners to become feasible. In the meantime, engineers and scientists must look for other ways to make planes more fuel efficient.

Most of the improvements that make airplanes more efficient are done through changing their design. These incremental design choices from airfoil shape, fuselage size, wingspan, and more have had huge effects on flight behavior. In addition, many of these design ideas have first been experimented on smaller planes before being implemented onto commercial airliners. In a similar vein, this experiment will test different iterations of wings and will model results for slow flying aircrafts. A wind tunnel was used for this purpose. When considering the scale, the wind tunnel's relatively slow velocity along with the small size of the wings helps carry out this very function.

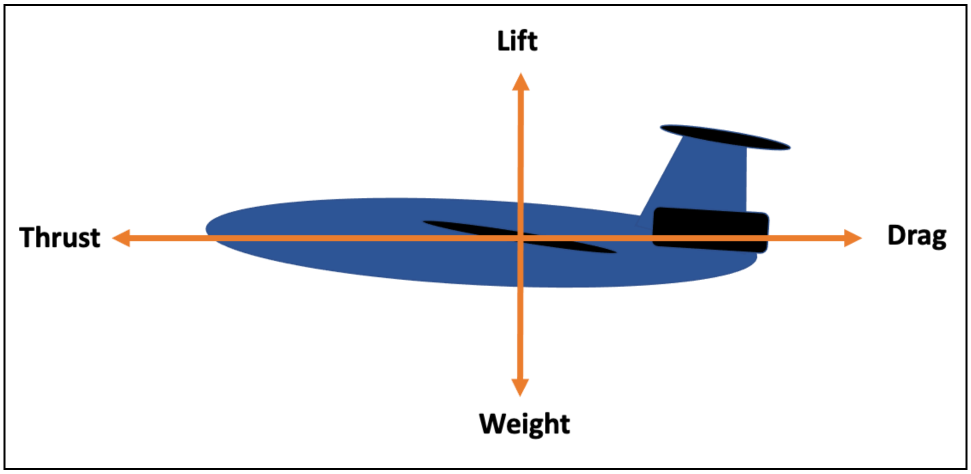

Figure 1. Four Forces Acting on a Plane.

Skybrary.Aero, 2022, https://www.skybrary.aero/sites/default/files/Four%20forces.png. 9 Dec 2022.

Previous research on this subject mainly focused on reducing drag. But this experiment, however, is looking for ways to increase lift. Lift, as seen in Figure 2 lift is the perpendicular force to drag and also plays a huge part in fuel efficiency. By allowing the plane to generate more lift through its wing design, it would rely less on its engine for that function thus making it more fuel efficient (Hall). There are three factors that this experiment will be testing for: wing thickness, wing sweep, and the proportion of the airfoils or whether the wings take a rectangular shape or a trapeal shape. All these factors have been heavily researched upon and their individual effects are already well known. However, the combination of these factors is what makes this experiment unique and could possibly open new paths of research in the industry

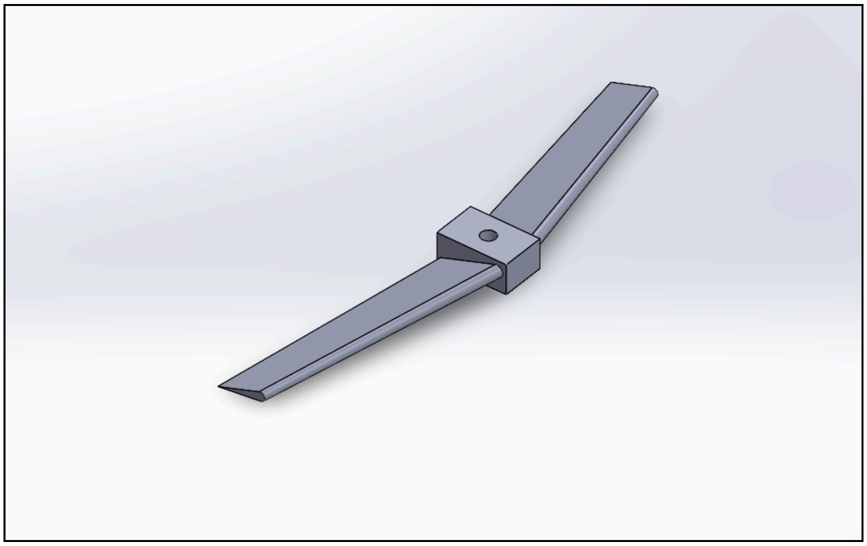

Figure 2. Standard Wing on Solidworks

Figure 2 above shows the finished product of the standard wing on Solidworks. The wings were printed out using Prusa Slicer and a 3d Printer. The wings were placed on a wooden dowel that was inserted into a hole. The hole was drilled into a piece of wood at a 10° angle which is the typical angle of attack that a plane will need to generate enough lift to take off according to Richard Satow of Boeing. The dowel went through a wind tunnel with the wings inside it.

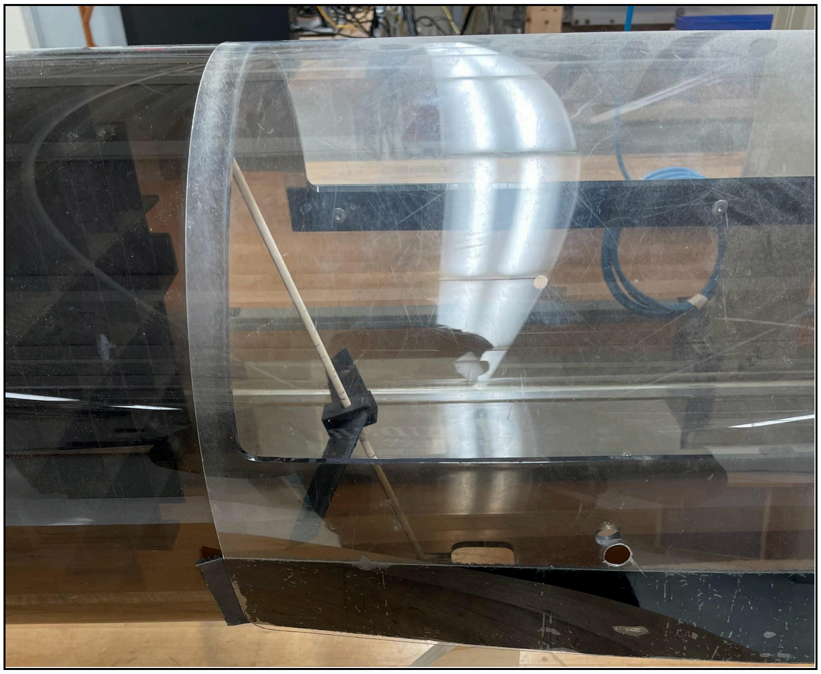

Figure 3. Experimental Set-up

A wind tunnel is a contraption for measuring the aerodynamic capabilities of certain objects. The one used in this experiment is a large tube with fans on both sides. The wind tunnel would be turned on and the wings would take flight. Once the wings stabilized at a given point, one person would hold onto the wing while the other person marked where the bottom of the center box was on the dowel. Figure 3 demonstrates the wings flying on the dowel as the wind tunnel is running.A caliper was then used to measure the distance from the mark to where the bottom of the center box would rest when the wind tunnel was turned off. The height that the pair of wings rose would model the amount of lift that they received.

With this data, this experiment was able to cross examine which factor or combination of factors had the greatest effect on lift. The results from this experiment would not only allow aerospace engineers to deduce which factors they should focus on, but also which configuration will result in the most fuel efficient planes.

Review of Literature

The main focus of this research revolved manipulating specific aspects of plane wings to test for which factors would generate the most lift. In particular, this project focused on small, slow flying aircraft. There are four main forces that act upon a plane that are important to understanding its flight behavior; lift, gravity, drag, thrust. The weight force pulls the plane down while the lift force pulls it up balancing out the weight force. The lift force is what keeps the plane in the air and can be generated by various parts, most notably the wings. The engines typically generate the thrust force which propels the plane forward, but in this experiment the plane will only move in one dimension which is up and down. While the plane is flying, the plane is opposed by air resistance. When an aircraft is moving through the air, the air molecules hit the wings in one direction causing lift in the other directions. This is due to Newton's 3rd law of motion, as the downward force pushes the wing upwards and thus creating more lift (Nancy). Figure 4 below visualizes how these four forces act on a plane during flight.

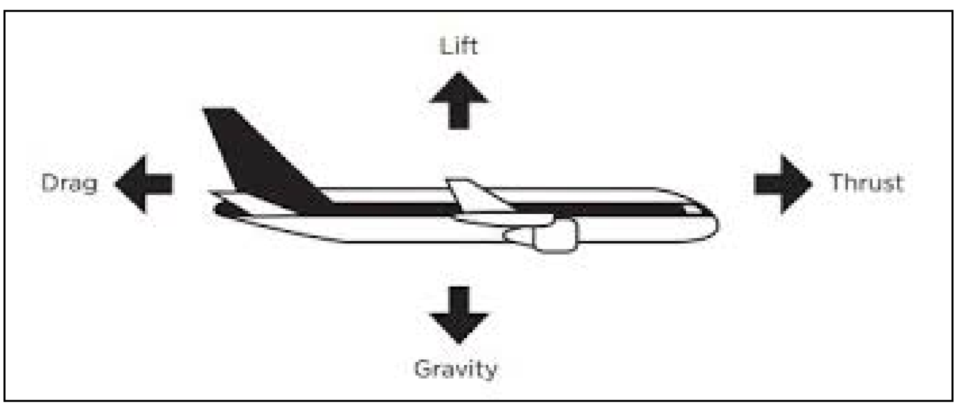

Figure 4. Four forces acting on a plane during flight.

"Four Forces Of Flight - Science World". *Science World*, 2022, https://www.scienceworld.ca/resource/four-forces-flight/. 7 Oct 2022.

To calculate lift, the equation F = ½ × Cl × r × v^2 × A , where CL is lift coefficient manipulated by the shape of the wing, r is the air density, v is velocity, and A is the area of the wing will be used (Nancy). To calculate drag, the equation D = ½ × Cd × r × v^2 × A. The variables in the drag equation are the same as those in the lift equation except for Cd, which is the coefficient of drag. Iterations of plane designs that are meant to increase lift could also increase drag. Designing planes requires balancing the net effect of these forces by looking for ways to increase lift while also minimizing the increase in lift.

The wings were designed in such a manner as to test for wing sweep while also fitting into the constraints of a Design of Experiment. The low displacement wing was the straight wing while the high displacement wing was the swept wing (See Appendix C). Most modern airliners have a wing sweep. Swept wings are better at cutting through the air with more efficiency. The sweep reduces the acceleration of the airflow over the wing as explained by Thomas Miller (See Appendix D). The air flow essentially becomes perpendicular to the chord causing spanwise flow as seen in Figure 5.

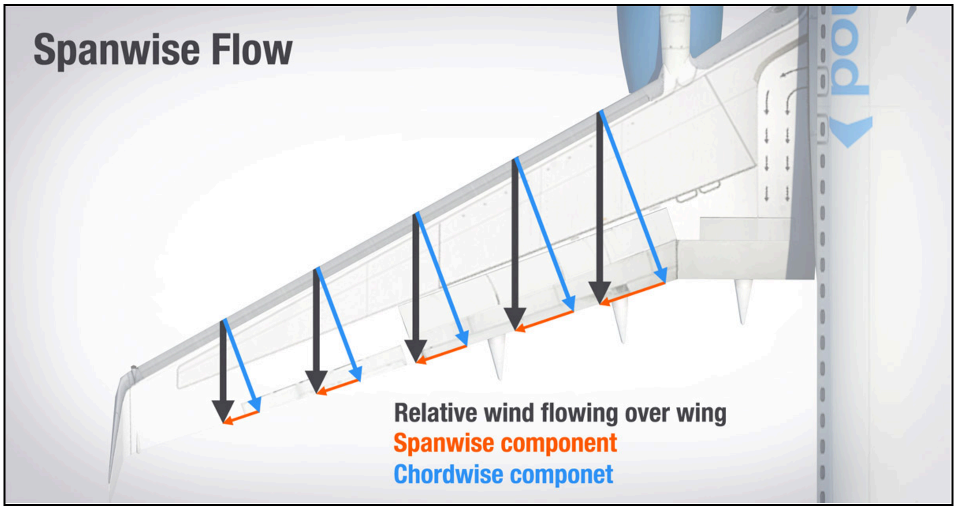

Figure 5. Spanwise Flow of a Swept Wing

Udris, Aleks. *Cdn.Boldmethod.Com*, 2022, https://cdn.boldmethod.com/images/learn-to-fly/aerodynamics/wing-sweep/spanwise-flow.jpg. 11 Dec 2022.

Only the parallel components of airflow accelerate. So by reducing the acceleration of the airflow, the sweep reduces the speed of the air pushing back against the plane. In other words, it reduces the drag. However, as Professor Miller warned, the reduction in airflow also means that the wings will generate less lift. This is especially true at low speeds as the plane is losing lift from both the reduction in lift and velocity. For this reason, it was hypothesized that the straight wings would generate more lift.

The effect of wing thickness also revolves around the airflow around the wing. Thicker airfoils push more air around it thus accelerating the airflow. The wings would experience more drag but would also generate more lift (Somers). A study done by Adson Agrico De Paula found that among similar symmetric airfoils, which is what this experiment is using, thicker wings tended to generate greater coefficient of lift values. That said, however, if the airfoil is too thick, the weight of the wings would weigh down the plane canceling out the increase in lift. In order to combat the added weight, the plane would have to fly at higher velocities. It was hypothesized that the thicker wings, although having the potential to generate more lift, would perform worse than the thin wings because the speeds in the wind tunnel are not fast enough.

Wing proportion affects another important wing characteristic which is wing area. In general, larger wings will generate more lift because they are able to move more air. In other words, the additional area means that more air molecules are colliding with the wing resulting in a larger net upward force (Benson).

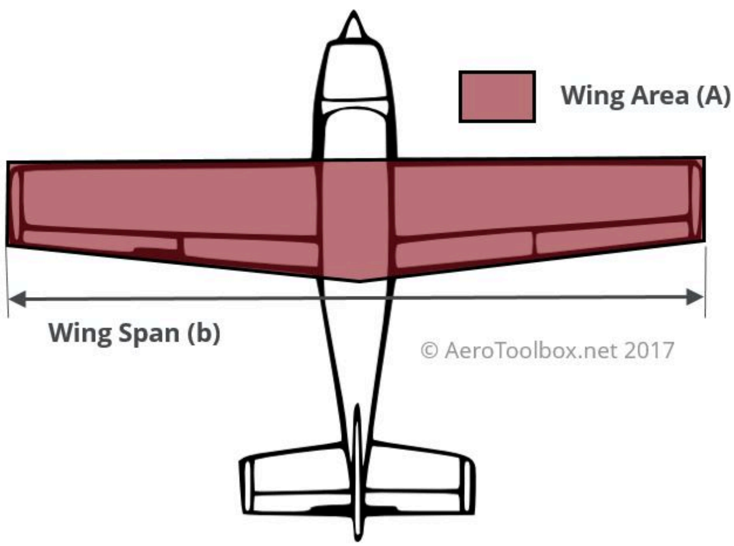

Figure 6. Wing Area

Wood, Andrew. *Aerotoolbox.Com*, 2022, https://aerotoolbox.com/media/uploads/2017/03/wing-area-definition.jpg. 11 Dec 2022.

Figure 6 depicts a smaller plane and its wing area highlighted in red. The outer sides of the wings are shorter than the inner side connected to the fuselage making the proportion uneven. This means that the wing has less area and thus generates less lift.

That said, however, there will be some point where larger wings will only drag down the plane. Drag is directly proportional to weight. So increasingly larger wing areas will bring about more lift and drag. In a similar vein to wing thickness, this means finding the sweet spot between stability and efficiency. That said, however, the wings being used in this experiment are relatively small. It was hypothesized that wing proportion would have a negligible effect on lift.

Problem Statement

Problem:

Which factors or combination of factors between wing sweep, thickness, and proportion will have the greatest effect on lift.

Hypothesis:

The thinner and no sweep wings will produce the greatest lift while proportion will have a negligible effect.

Data Measured:

The independent variables of this experiment was the manipulation between wing sweep, thickness, and proportion. The wing pairs were designed in Solidworks to ensure the most accurate measurements in the design of the wings. Inside Solidworks various wings were designed all to fit into the different combinations of wings to be tested for this experiment and then 3D printed. The dependent variable measured in this experiment was the amount of lift generated, or distance that the wings rose. This maximum distance was then marked and measured from where the wing pair naturally sat in the wind tunnel to receive the distance the wing pair rose. The distance was measured in millimeters since the wind tunnel is limited in space and measurements are appropriate to be more accurate.

In this experiment, it was appropriate to conduct a three factor design of experiment (DOE) since there are many factors that can be changed. There only needed to be 11 trials for every single DOE which means that this experiment can be repeated many times. From there, the individual and interaction effects were found.

Experimental Design

Materials:

3D Printer
Wing Mount(See Appendix B)
Sharpie/Pen
Standard Wing Pair
Wooden Dowel (⅛ inch)
Caliper
(8)Experimental Wing Pairs (See Appendix C)
MMSTC Wind Tunnel
TI-Nspire Calculator

Procedure:

1. Go to an open area inside a building where trails can be conducted.
2. Before using the wind tunnel ensure that the area inside the tunnel is clear of any debris that can get stuck within the fans.
3. Place the wooden base underneath the opening on the bottom side of the wind tunnel and then insert the wooden dowel through the tunnel and into the base. The wooden dowel might need to be adjusted according to the maximum height restricted by the wind tunnel.
4. Using the random integer feature on the TI-Nspire calculator, randomize the order of the 11 trials, making sure the first, sixth, and eleventh trials are standard trials and that there are no repeating numbers in the series of randomized trials.
5. To conduct trials place the according wing pair, given from the previous step, and slide onto wooden dowel.
6. Turn both of the fans of the wind tunnel to the high speed setting.
7. Wait between 5-10 seconds until the wing pair is consistently gliding in one location on the dowel.
8. Grab the wing pair ensuring that there is minimum movement and turn off both of the fans of the tunnel.
9. Using a pen or pencil mark right underneath the wing pair and unto the wooden dowel for measurements.
10. Release the wing pair and find its resting position on the wind tunnel and measure from the bottom of the wing to the marked position from the previous step and record the data found into a spreadsheet.
11. Repeat steps 5-10 repeatedly until all trials in the design of the experiment (DOE) are completed.
12. Repeat previous steps two more times for a total of three DOE runs.

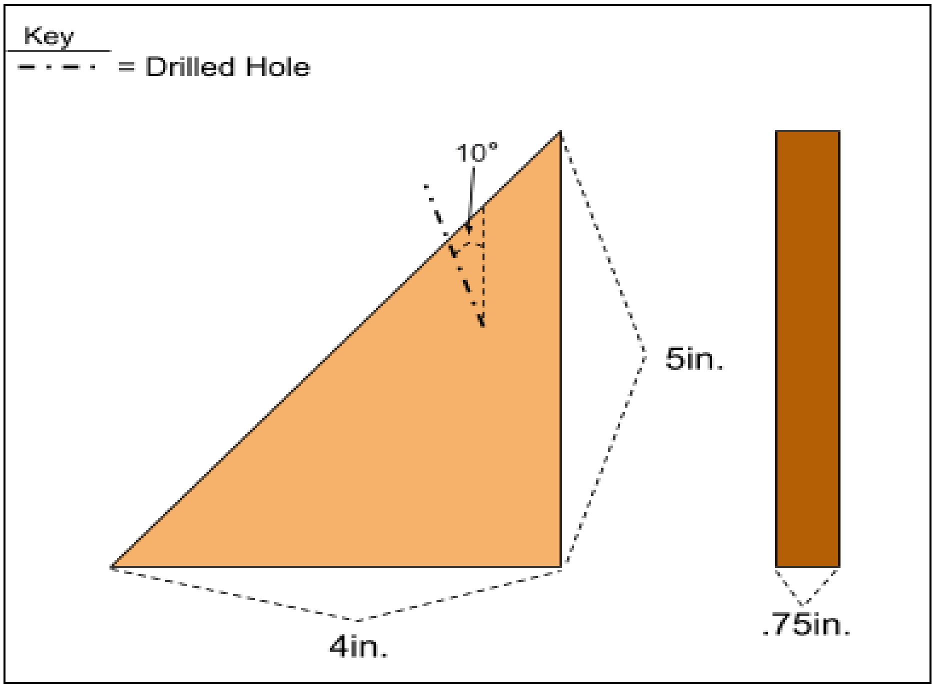

Figure 7. Wing Mount Net Diagram

Figure 7 is a net diagram for how the wing mount is constructed. The wing mount can also be seen in Figure 8.

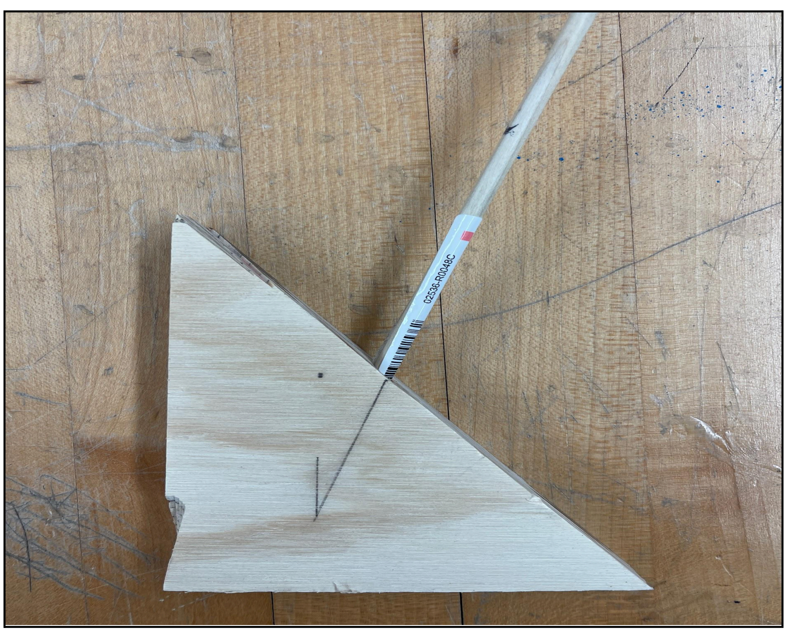

Figure 8. Wing Mount

Figure 8 illustrates what the wing mount looks like. The wings will be placed onto the wooden dowel the ten degree angle backward to produce lift.

Figure 9. Wing Mount Setup in Wind Tunnel

The wooden dowel from the wing mount is set through a bottom hole of the wind tunnel. The setup for this experiment is the same for all the trails. So every trial was conducted like this.

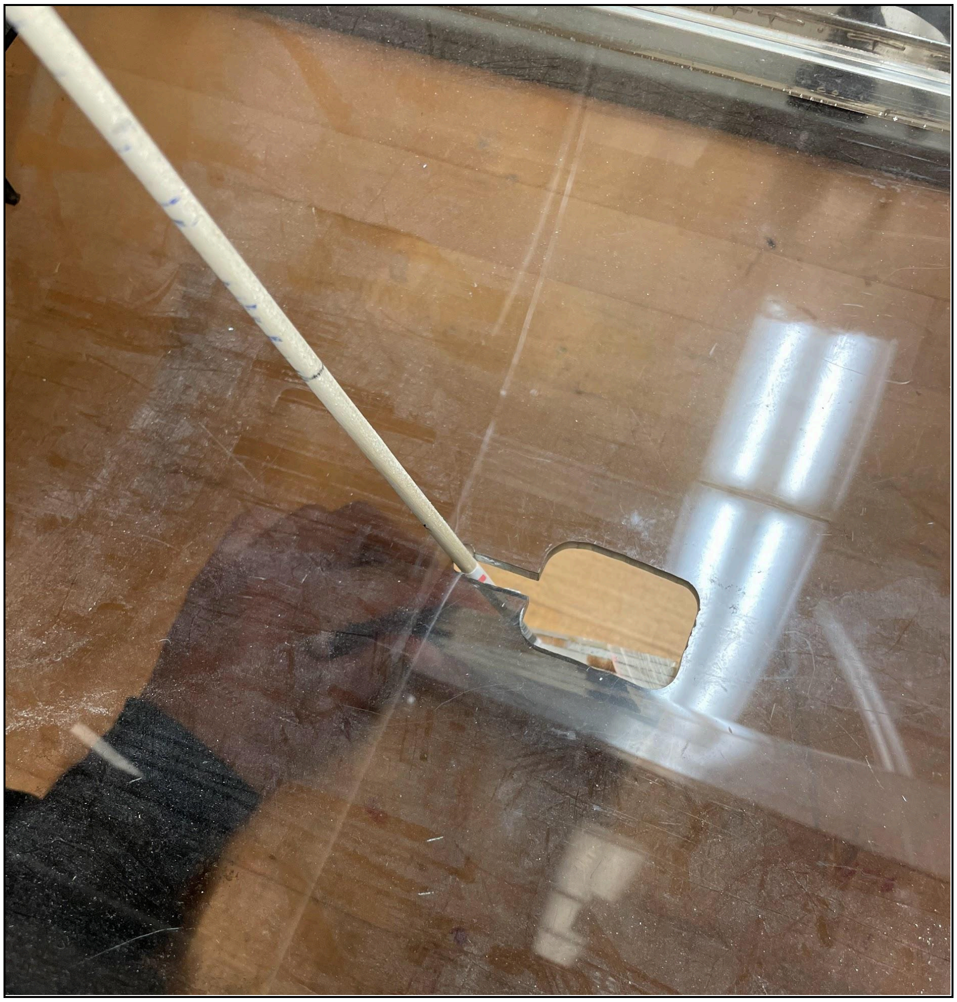

Figure 10. Setup for Data Collection

At the beginning of every trial, it was ensured that the wooden dowel was inserted through the notch shown in Figure 10 and pushed as far back as possible to make the placement of the wings and mount had little to no difference in between trials.

Figure 11. Wing Flying on Dowel

Figure 11 shows the standard wings flying on the dowel after the wind tunnel was turned on. The bottom of the middle box was marked on the dowel. The difference from that mark to where the bottom of the middle box was resting before the wind tunnel was turned on is what is being used to measure height.

Data and Observations

Table 1
Factors and Values

Factors	(-) Values	Standards	(+) Values
Thickness	.15mm	.10mm	.05mm
Proportion	1	.75	.5
Displacement	2in	1in	0in

Table 1 shows the three factors and their high (+), low (-), and standard values.

Table 2
DOE Runs

Randomized Trials	Factors	Run 1	Run 2	Run 3
	Thickness, Proportion, Displacement	Height (mm)		
1	standard	32.42	35.27	36.2
5,2,4	(+, +, +)	0	0	0
10,4,9	(+, +, -)	0	0	0
3,7, 7	(+, -, +)	16.98	15.06	15.37
9,9,19	(+, -, -)	26.11	28.04	30.25
6	standard	26.8	31.98	40.02
4,10,5	(-, +, +)	61.53	82.9	65.8
7,5,3	(-, +, -)	200	200	200
8,8,2	(-, -, +)	60.4	62.56	63.45
2,3,8	(-, -, -)	104.3	100.2	99.85
11	standard	37.82	38.36	31.07

Table 2 shows the results from all three Design of Experiments (DOE) runs.

Table 3
Averages of DOE Runs

Randomized Trials	Factors	Average Height (mm)
	Thickness, Proportion, Displacement	
1	standard	34.65
5,2,4	(+, +, +)	0
10,4,9	(+, +, -)	0
3,7, 7	(+, -, +)	15.80
9,9,19	(+, -, -)	28.13
6	standard	32.93
4,10,5	(-, +, +)	70.078
7,5,3	(-, +, -)	200
8,8,2	(-, -, +)	62.134
2,3,8	(-, -, -)	101.44
11	standard	35.75

Table 3 shows the averages of all the different combinations from the three DOE runs. The range of the outputs varied from 0 mm, meaning that the wings did not rise at all, to 200 mm, meaning that the wing flew off the dowel.

Table 4
Observations

Doe/Trial	Combination	Observation
1,2,3	+,+,+ and +,+,-	Every trial with one of these two combinations of wings, would always result in 0mm. Tried many different ways but always no flight.
1,2,3	-,+,-	The wing would fly out of the wooden dowel and would also spin around. Redid the trial several times to check but ultimately concluded that the wing will always fly out.
Doe/Trial	**Combination**	**Observation**

2/3	-,-,-	The wing faced a lot of turbulence and would spin in place while rising. After trying to set the wing straight, it was found that the wing was stable at around 100 mm.
3/5	-,+,+	Redid this trial several times because the wing kept spinning out of place and falling back down.

Table 4 documents any observations or notes made about specific trials such as unexpected occurrences that lead to redoing trials.

Figure 12. Experimental Setup

Figure 12 depicts how each of the trails were done and set up. The wooden triangle and the dowel were used to hold the wings stationary until the wind was activated where it would rise.

Data Analysis and Interpretation

The basis of this experiment revolved around the manipulation of the airfoils. This experiment tested for thickness, proportion, and displacement of the airfoils. The dependent variable, the height the wings rose on the wooden dowel, was measured using a caliper and in millimeters.. A three-factor Design of Experiment (DOE) was used in order to test the factors' individual effects and interaction effects in pairs and see which of the effects were significant. To obtain more accurate results, the DOE was repeated 3 times in order to eliminate slight variations between runs that might affect the final set of data. Each corresponding trial in the 3 runs were averaged, which all final calculations were based off of. The trial order of each DOE was randomized using TI-NSpire Software to spread out the effects of any confounding variables or bias. Standard trials in each DOE run remained in the same spots throughout all runs at order 1, 6, and 11. This was done to measure the variability due to any confounding variables throughout the runs. The hole was drilled into a piece of wood at a 10 degree angle. The wooden dowel was inserted into the hole and kept in its exact position for the entirety of the experiment. The dowel was centered in the wind tunnel to make sure the wings were centered. The wind tunnel had the same settings for every trial. A caliper was used to measure highly accurate results. The dowel was placed in a slot which made it center everytime and also made the experiment easily replicable.

One Factor Effects

Table 5
Grand Average

Trials			Average Height Airfoil Rose (mm)
Thickness	Proportion	Angle	
(+)	(+)	(+)	0
(+)	(+)	(-)	0
(+)	(-)	(+)	15.80
(+)	(-)	(-)	28.13
(-)	(+)	(+)	70.08
(-)	(+)	(-)	200
(-)	(-)	(+)	62.14
(-)	(-)	(-)	101.44
Grand Average			57.70

Table 5 shows the average height that each wing rose on the wooden dowel but excluding the standards. The grand average of the data, 57.70 mm, is also shown, which was found by adding all the averages up and dividing by the number of different trials.

Table 6
Effect of Thickness

Effect of Thickness	
(-) Values	(+) Values
70.08	0
200	0
62.14	15.80
101.44	28.13
Avg = 108.42	Avg = 10.98
Effect Value = -97.44	

Table 6 shows the averages of low and high values of thickness as calculated by adding the values of the low and high runs for airfoil thickness and dividing by the number of different trials (4). This method is used to find the individual effect values of all three independent variables.

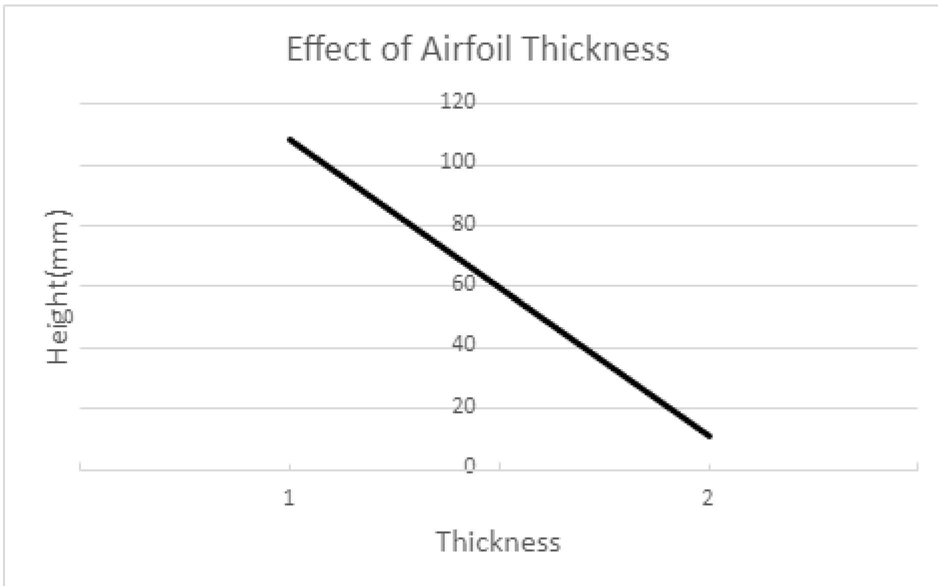

Figure 13. Effect of Thickness

Table 6 and Figure 13 show the effect of the low and high values of airfoil thickness on the height of the wings. The effect value of thickness, -97.44, was determined by subtracting the high value of 108.42 from the low value of 10.98 in Figure 13. The negative effect value and the downward sloping effect line suggest that thicker airfoils cause less lift. The relatively large effect value also suggests that airfoil thickness played a major role in how high the wings rose.

Table 7
Effect of Proportion

Effect of Proportion	
(-) Values	**(+) Values**
15.80	0
28.13	0
62.14	70.08
101.44	200
Avg = 51.88	Avg = 67.52
Effect Value = 15.64	

Table 7 shows the averages for the high and low values for the effect of proportion and the effect value.

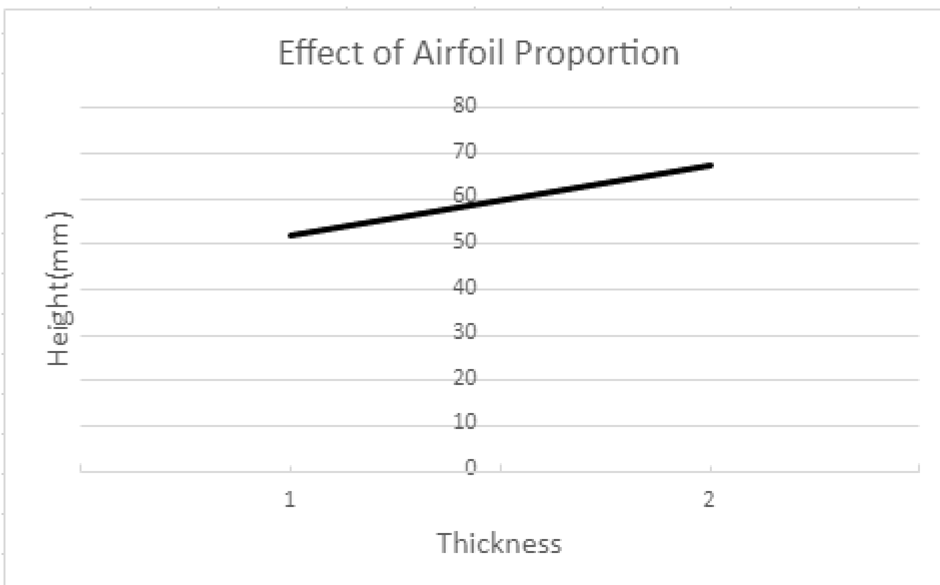

Figure 14. Effect of Proportion

Figure 14 and table 7 demonstrate the effect on airfoil proportion on height. The average for the low values was 51.88 and the average for the high values was 67.52 resulting in an effect value of 15.64. The positive effect value shows that on average, height increases with the airfoil proportion. However, the effect value is relatively small as compared suggesting that proportion may not play that big of role when it comes to generating lift.

Table 8
Effect of Displacement

Effect of Displacement	
(-) Values	**(+) Values**
0	0
28.13	15.80
200	70.08
101.44	62.14
Avg = 83.39	Avg = 37.00
Effect Value = -45.39	

Table 8 shows the averages for the high and low values for the effect of displacement and the effect value.

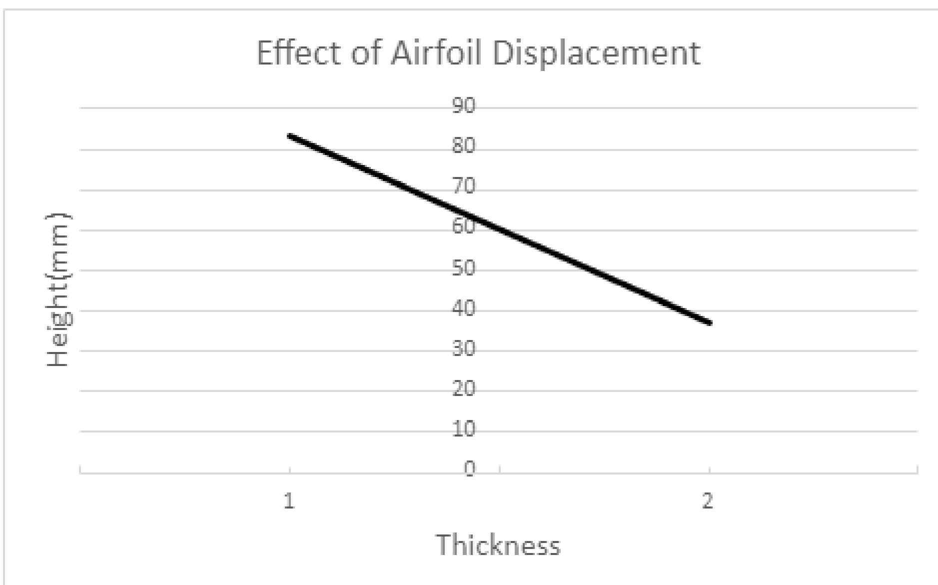

Figure 15. Effect of Displacement

Figure 15 and table 8 demonstrate the effect on airfoil displacement on height. The average for the low values was 83.39 and the average for the high values was 37.00

resulting in an effect value of -45.39. Similar to the effect of the airfoil thickness, the downward sloping effect line and negative effect value suggest that height decreases on average as displacement increases but in a smaller magnitude.

<u>Two Factor Interactions</u>

Table 9
Interaction Effect of Thickness and Proportion

Thickness and Proportion			**Proportion**	
			(-)	(+)
Thickness	Line Segment Solid	(+)	21.97	0
	Line Segment Dotted	(-)	81.79	135.04
Interaction Effect Value = -15.68				

Table 9, above, shows the high and low values between thickness and proportion used to determine the interaction effect value.

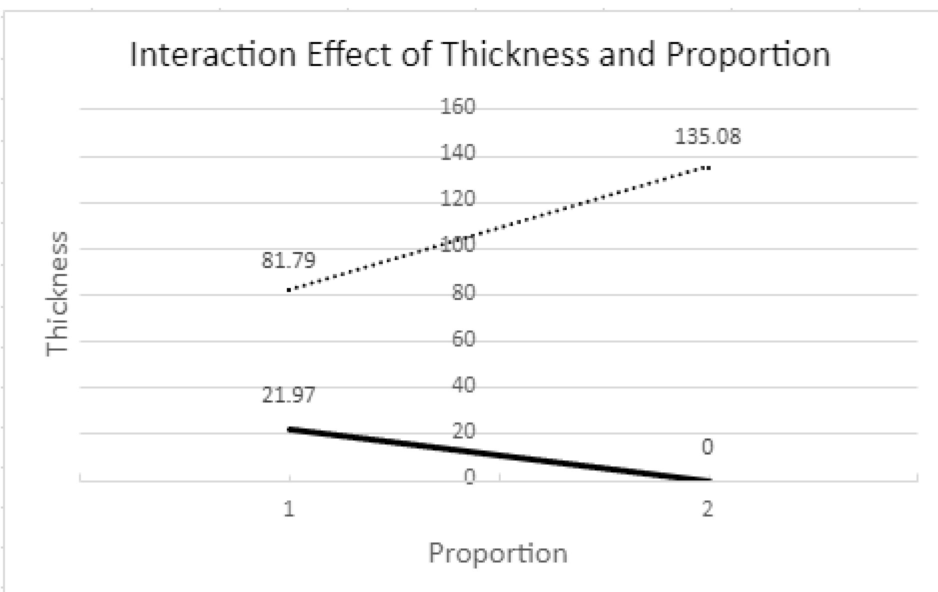

Figure 16. Interaction Effect of Thickness and Proportion

Table 9 and Figure 16, above, show the interaction between thickness and proportion. The interaction effect value was found by subtracting the slope of the low thickness values (dotted line) from the slope of the high thickness values (solid line). Since the lines are not parallel, there might be an interaction as the rate of change of the height as proportion increases depends on whether thickness is high or low. The data suggests that low thickness combined with an even proportion leads to the most amount of lift.

Table 10
Interaction Effect of Thickness and Displacement

Thickness and Displacement			**Displacement**	
			(-)	(+)
Thickness	Line Segment Solid	(+)	14.07	7.9
	Line Segment Dotted	(-)	150.52	66.11
Interaction Effect Value = -44.39				

Table 10, above, shows the high and low values between thickness and proportion used to determine the interaction effect value.

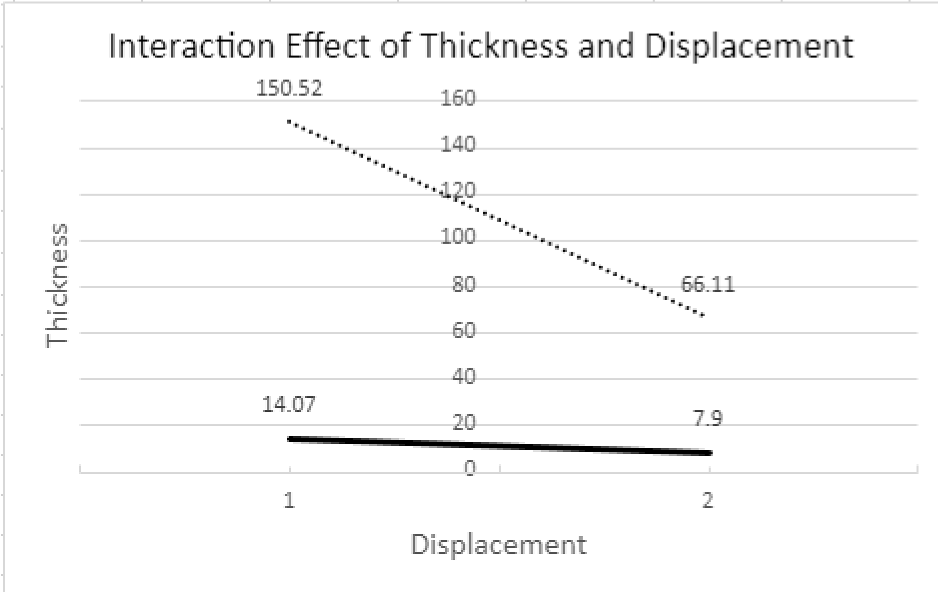

Figure 17. Interaction Effect of Thickness and Displacement

Table 10 and Figure 17, above, show the interaction between thickness and displacement. The interaction effect value was found by subtracting the slope of the low thickness values (dotted line) from the slope of the high thickness values (solid line). Since the lines are not parallel, there might be an interaction as the rate of change of the height as displacement increases depends on whether thickness is high or low. The data again suggest that low thickness leads to the best results. In fact, low thickness combined with low displacement led to the highest effect value in this study.

Table 11
Interaction Effect of Proportion and Displacement

Proportion and Displacement			**Proportion**	
			(-)	(+)
Displacement	Line Segment Solid	(+)	100	25.04
	Line Segment Dotted	(-)	64.79	38.82
Interaction Effect Value = -19.50				

Table 11, above, shows the high and low values between thickness and proportion used to determine the interaction effect value.

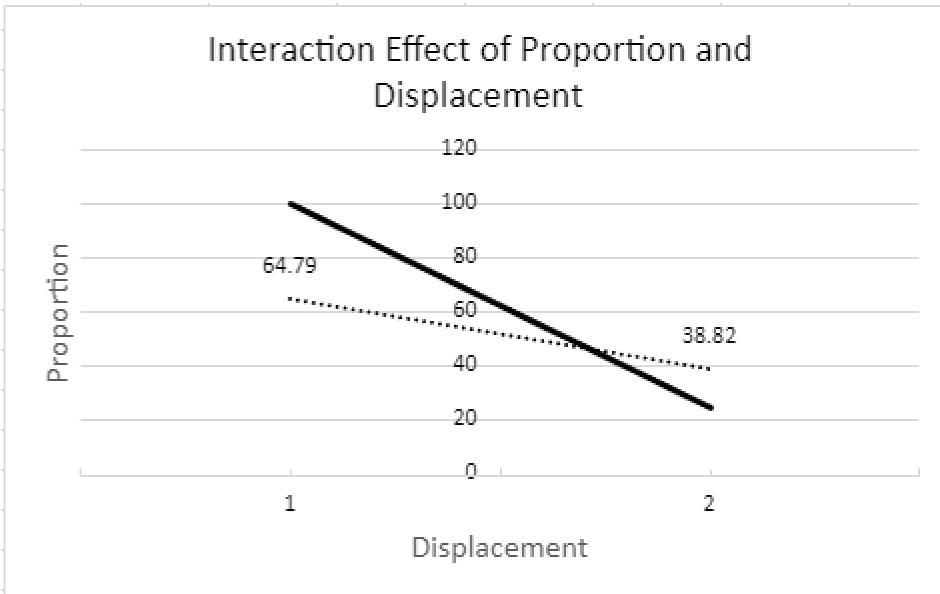

Figure 18. Interaction Effect of Proportion and Displacement

Table 11 and Figure 18, above, show the interaction between proportion and displacement. The interaction effect value was found by subtracting the slope of the low proportion values (dotted line) from the slope of the high proportion values (solid line). Since the lines are not parallel, there might be an interaction as the rate of change of the height as displacement increases depends on whether proportion is high or low. In contrast to its individual effect, higher proportions led to less lift when looking at the interaction with displacement. The best result was recorded when proportion was low and displacement was high. This suggests that planes with angled wings should have their second airfoil be much smaller than the primary airfoil.

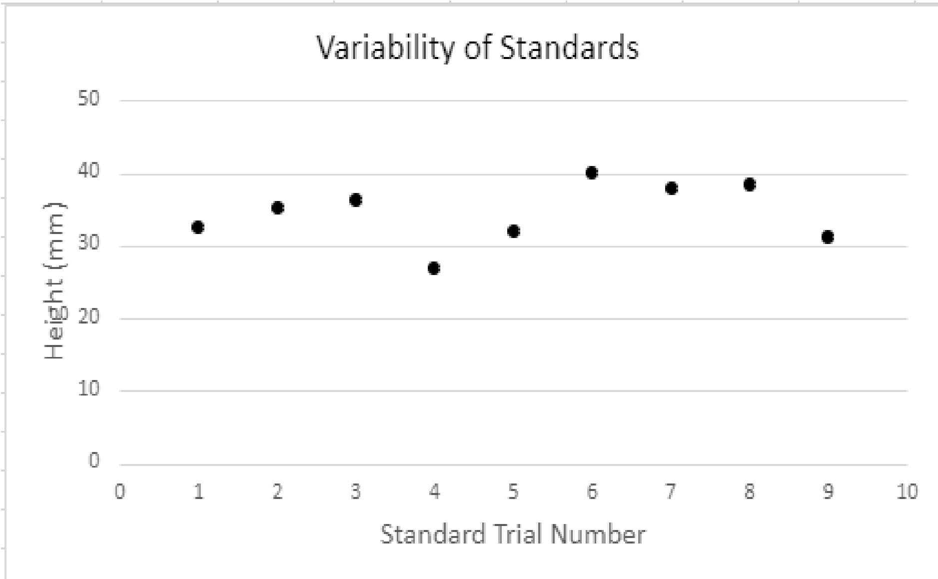

Figure 19. Variability of Standards

Figure 19, above, shows the variability of the standard trials' data collected. Judging from the graph, there does not seem to be any pattern or trends occurring over time.

Table 12
Average Standard Trials

Standard Trial #	Average Height
1	34.65
6	32.93
11	35.75

Table 12, above shows the averages of all the standard trials (the first, sixth and eleventh trials) from each of the five runs. In order to conduct the test of significance from the DOE results, the lowest average standard was subtracted from the highest average standard. This resulted in a range of standards of 2.82mm.

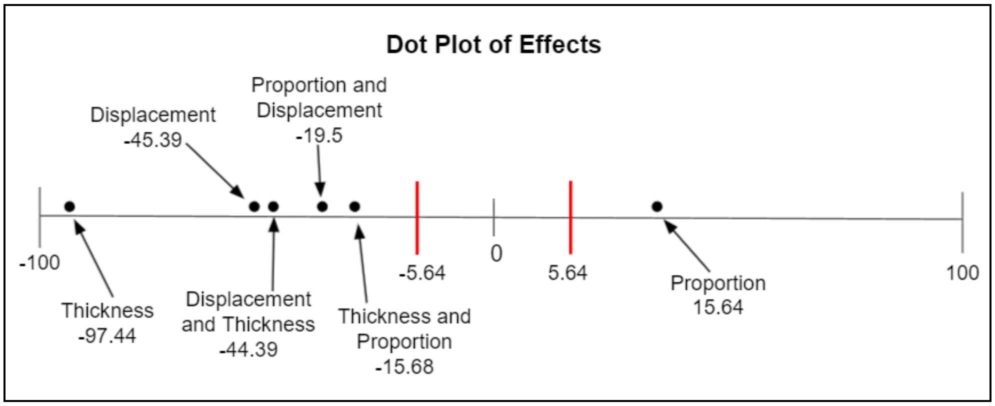

Figure 20. Dot Plot of Effects

Figure 20 shows a dot plot of the effects of each factor and combination of factors and their effects which are labeled accordingly. In order to determine which variable effects were significant, the range of the average standards, our range of standard value of 2.82mm was doubled to get 5.64 and then labeled as red lines or "gates" at ± 5.64. Any dots that fall between the gates are deemed insignificant, while any outside of the gates are significant. As Figure 20 shows all of the factors in this experiment were deemed to be significant and therefore used in the prediction equation (see Appendix A).

It was found that thickness had the greatest effect on how high the wings rose. The thinner wings led to the best results especially when the wings were not angled back. However, these wings also faced plenty of turbulence in the wing tunnel. Displacement had the second greatest effect where the non-angled wings had performed better than the angled wings. Proportion had the lowest effect but was the only factor that positively correlated with height. However, high proportions and high thickness led to the worst results as those planes did not fly at all. All in all, the data suggests that thinner wings that are not angled back will lead to the most amount of lift for low speed aircraft.

Conclusion

This experiment looked at how manipulating different aspects of a plane's wing and airfoil effect the amount of lift an aircraft would experience when flying at low speeds. The factors were the thickness of the airfoil, the proportion of the airfoil on the edge of the wing to the airfoil connected to the fuselage, and the displacement of these two airfoils which changed the angle of the wings. The wings were designed on Solidworks and 3D printed with the aid of Prusa Slicer. The wings came in pairs with a box in the middle acting as a pseudo fuselage. The pair of wings were placed in a wind tunnel with a rod going through the box. The wind tunnel would be turned on and the wings would fly up the pole which was ultimately what this experiment was testing for. The height the pair of wings rose modeled the amount of lift the wings experienced. The wings that generated the most amount of lift rose the furthest. A 3 factor Design of Experiment was then used to analyze the data. The purpose of this experiment was to test for which combination of the factors stated above would lead to the most amount of lift.

It was originally hypothesized that the thinner wings that were not angled back would produce the most lift. This hypothesis was accepted as the wings with one or both of these features rose higher up the rod on average. Furthermore, the wings with these features produced the greatest average results as those two wings rose up to 101.437 mm and 200 mm on average respectively. Proportion was not taken into account as it was hypothesized that it would not have that as great of an effect. This inference was partially true as proportion was included in the three smallest effect values in magnitude of 15.64, -15.68, and -19.5. However, between the two best performing wings, the wings with the equilateral proportion rose twice as far as compared to the wings with the low proportion.

Wing thickness had by far the largest effect with an effect value of -97.44. All the thinner wings performed much better than their thicker counterparts. Displacement had the second largest effect with an effect value of -45.39. The negative values indicate that the wing size and distance rose vary inversely. This means that the thicker wings generated less lift on average throughout this experiment. The swept back wings performed worse on average. These results suggest that low speed aircraft should be designed with thin wings which can maximize lift but also carry the aircraft's weight. The wings should also not be angled back and be kept straight. This might seem contrary to basic aeronautical engineering principles as most planes have swept back wings. However, the reason why many jets and commercial airliners have swept wings is because those aircraft fly at high speeds (Bagley). This design decision can be further explained by the lift equation.

Lift is the product of the coefficient of drag, wing area, velocity squared, and fluid density all divided in half (Benson). According to the lift equation, lift is proportional to velocity squared. Swept wings are meant to reduce drag but end up also reducing lift. However, the loss in lift is made up by the increase in velocity.

An interesting aspect of this experiment is how the effect of proportion changes depending on the other variables. By itself, higher proportion wings led to greater lift. This is also explained by the lift equation as greater proportion means a greater area which is directly proportional to lift. That said however, the interaction effects that involved proportion were both negative. Take for example the two best performing wings mentioned before. The higher proportion wing led to the better results. But when both the thickness and the displacement were kept high, the low proportion wings performed better.

Figure 21. Cessna Aircraft

"Top 3 Things You Should Know About Light Aircraft". *Acornwelding.Com*, 2022, https://www.acornwelding.com/blog/post/things-know-about-light-aircraft/. Accessed 28 Nov 2022.

Figure 22 is an example of a small, slow flying aircraft used mostly for recreational purposes. The wings are not swept back and are relatively thin. The size of the outside airfoil is equal to the size of the inside airfoil giving the wing an even proportion. Because of its low flying speeds, the plane would need to rely on other factors for lift which is why its designers used an even proportion to maximize its area.

Figure 23. Large Aircraft

Naypong. "Aerial Top View Of Airplane Isolated On White Background With...". *Istock*, 2022, https://www.istockphoto.com/photo/aerial-top-view-of-airplane-isolated-on-white. Accessed 28 Nov 2022.

Figure 23 is an example of a typical commercial airliner. The wings are swept back and the outside airfoil is much smaller than the inside airfoil giving the plane a very low proportion. Airliners fly at much faster speeds which is why they sacrifice lift through the wing area to get lift through increased velocity.

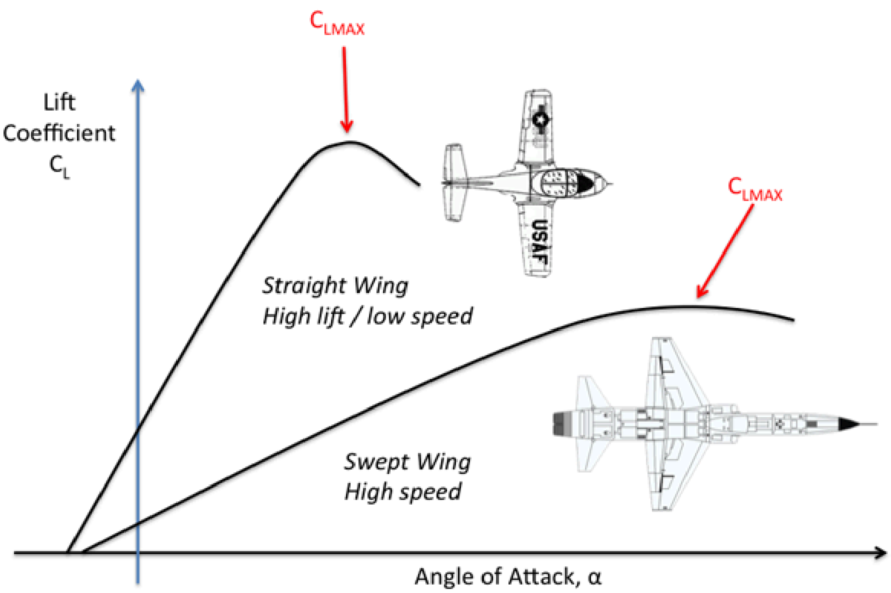

Figure 24. Graph of Straight Wing Lift Curve and Swept Wing Lift Curve.

"Stall Recovery". *Code7700.Com*, 2022,

https://code7700.com/stall_recovery.htm#gsc.tab=0. Accessed 28 Nov 2022.

Other researchers have come to the same conclusion. According to Bruno Moorthamers, the slope of the lift curve, as seen in Figure 24, for straight wings flattens out before the swept wing. The straight wing achieves a higher lift coefficient value and achieves it a lower angle of attack. Keep in mind, the lift coefficient is only a part of the lift equation where velocity also comes into play. Also keep in mind that the angle of attack in this experiment was kept constant which might have given an advantage to the straight wings.

Another observation made during data testing was the turbulence some of the wings ran into. Oddly enough, the two best performing wings were also the least stable on the rod. Part of this can be attributed to the thinness. But more notably, the wings were not swept back. In fact, the swept wings were the most stable on average. Most current researchers have also come to the same conclusion. A project led by Zhenropng Jing analyzed the instability of a specific type of wing when swept. The researchers found that the swept wings consistently ended up in a more stable position than the non-swept wings. With swept wings, a plane is able to move the center of lift forwards or backwards to bring itself back into equilibrium.

The wings were printed using PLA which might have affected some of the results. In particular, it might explain why thickness played the largest role. Using foam or metal might be more ideal when revisiting this experiment. Furthermore, the wings were tested without an appropriate fuselage to scale. This most definitely could have affected the stability aspect of the wings. If, for example, a fuselage modeled after a Cessna was used, then the straight wings might have been more stable in the air. Future iterations of this experiment should pick a certain type of plane to focus on and then model the fuselage and the wings from there. The wind tunnel limited some of the testing that could have been done. The best performing wing actually flew out of the rod and hit the top of the wind tunnel. This means that its true flight potential might be much greater than what was assumed therefore skewing the data against it. For the purposes of this experiment, the value of 200 mm was given to it as that is the approximate distance between the wing's resting point and the top of the wind tunnel. The wind tunnel's speed was not relatively fast. When scaling the size of the wings and the speed of the wind tunnel, this experiment could only test for slow flying aircraft such as the Cessna. To achieve a more comprehensive understanding of how certain wing characteristics affect flight behavior, a future experiment should be done in a high speed wind tunnel with bigger wings, preferably made out of aluminum.

There is still the question of how a forward sweeping wing would perform in this experiment. Although uncommon, forward swept wings have shown signs of being more stable in the air. Since the thinner wings performed better, it could still be possible that even thinner wings could rise higher and generate more lift.

Future research into this subject will be vital for the future of the aviation industry. Smaller, recreational planes will need to find ways to become more efficient through generating more lift. New research looking at how changing different aspects of the wings and airfoils will optimize flight will be vital for this breakthrough.

Appendix A: Prediction Equations

Y = 59.7 + -97.44 (Thickness) + 15.64 (Proportion)+ -45.39 (Displacement) + -15.68 (Thickness and Proportion) + -44.39 (Displacement and Thickness) + -19.5 (Proportion and Displacement) + "noise"

Figure 25. Prediction Equation

Figure 25, above, displays the prediction equation and includes the grand average plus all factors and interaction effects analyzed. This equation is broad and does not discriminate between insignificant and significant factors.

Y = 59.7 + -97.44 (Thickness) + 15.64 (Proportion)+ -45.39 (Displacement) + -15.68 (Thickness and Proportion) + -44.39 (Displacement and Thickness) + -19.5 (Proportion and Displacement) + "noise"

Figure 25. Parsimonious Prediction Equation

The Parsimonious Prediction Equation only takes into account the significant factors. In this experiment, every individual effect and interaction effect was deemed significant. Due to this, the Parsimonious Equation is the same as the original Prediction Equation.

Appendix B: Wing Mount

Materials:

(1) Piece of Wood (2x4) (Optional)
Chop Saw
Drill
Plywood (¾" x 4" x 5")
Wooden Dowel (⅛")
(2)Screw Fasteners (6")(Optional)
Pencil
Protractor

Procedure:

1. Before operating any machinery or working with fast moving parts, please refer to safety manuals provided by the respective manufacturer and assure safety glasses are worn
2. Find or cut a piece of plywood, using a chop saw or other appropriate equipment, into a triangular shape with the length of 4 inches, the height of 5 inches, and approximate thickness of ¾ inch.
3. Take a protractor and place onto the 5 inch side, or the height.
4. From there measure and mark a 10 degree angle with a protractor relative to the vertical, like illustrated in Figure 7 and 8, with a pencil.
5. Take a drill bit that is smaller than ⅛ inch to create a pilot hole into the wood at the 10 degree angle marked in the previous step.
6. Take the appropriate ⅛ inch bit, or bit that is the same size as the wooden dowel, and redrill into the hole previously made.
7. Insert the wooden dowel into the drilled hole and ensure that the wooden dowel has a tight fit. Make adjustments to the hole as needed
8. (Optional) Take extra 2x4 pieces of wood and screw fasteners and attach unto the wing mount so that the base of the mount has more stability and will not move.

Appendix C: Experimental Wing Pairs

Materials:

SolidWorks

3d Printer (Prusa Slicer)

Procedure:

1. On SolidWorks, open up a new part.
2. Select the sketch feature and sketch on the top plane.
3. Draw a 1.20" x 0.5" box with the longer side being parallel to the x-axis.
4. Select the Boss Extrude feature, select direction to blind, and set distance to 0.5".
5. Select the top of the box and click the sketch feature.
6. Draw a semicircle on the edge of the box connected to the front plane.
7. Set the radius to 0.25" and center the semi circle along the x-axis.
8. Select the Cut Extrude feature and set direction to Through All to create a hole.
9. Create a new plane on the edge of the box by offsetting the front plane by 0.5".
10. Click the new plane and select the sketch feature.
11. Draw the airfoil as depicted in Figure 26 while making sure it is centered both vertically and horizontally and that the line is 1" while the radius of the semi-circle is 0.1".
12. Create a new plane that is offset from the front plane by 6.50".
13. Repeat steps 10 and 11 but multiply the length of the line and the radius of the semi circle by 0.75 as prescribed for the standard wing.
14. Offset the distance of the center of the semicircles for both airfoils by 1" in order to create the wing sweep.
15. Select the Lofted Boss/Base Feature.
16. For profiles, select an edge on the original airfoil and select an identical edge on the offset airfoil to create the wing.
17. Select the Mirror feature, select the front plane as the mirror plane, and select the wing and the box as bodies to mirror to create the pair of wings.
18. For the high and low thickness wings, set the radius in step 11 to 0.15" and 0.05" respectively.

19. For the high and low proportion wings, multiply the length and proportion in step 13 by 1 and 0.5 respectively.

20. For the straight and swept wings, set the offset distance in step 14 by 0” and 2” respectively.

21. Save the part as a Step File and make sure to appropriately name the file.

22. Open the Prusa Slicer application.

23. Click file and import the Step File onto the base.

24. Set filament to Pusament PLA, supports to everywhere, infill to 20%, and print settings to 0.15 mm QUALITY.

25. Rotate the part so that the wings are facing up.

26. Click Slice Now and then export the G-code onto a SD Card.

27. Take the SD card and insert it into the 3d printer.

28. Use the knob to select the appropriate set of wings.

29. After printing, use a file to get rid of the supports.

30. Repeat all steps for all nine wings.

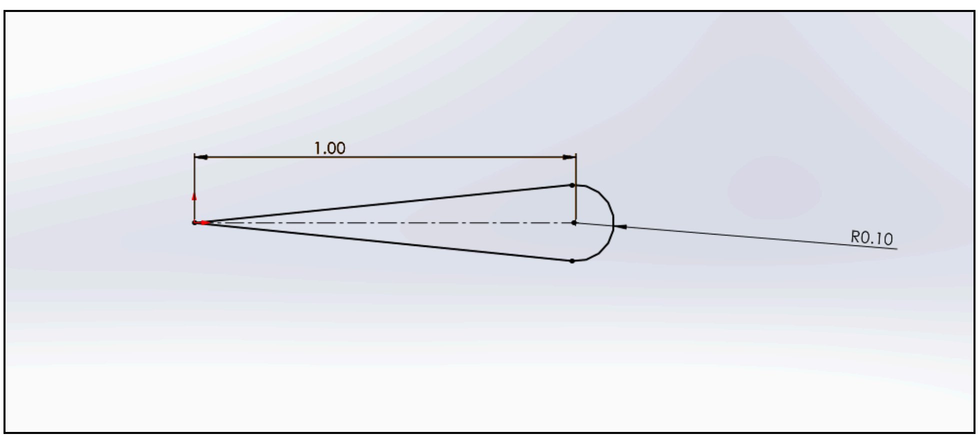

Figure 26. Airfoil thickness

The airfoils were of a simple shape and were drawn using two straight lines and a semi circle. For the sake of this experiment, the center of the semi-circle will be defined as the airfoil’s origin point. The distance from the vertex to the airfoil’s origin point is 1”. The radius of the semi circle was manipulated to change the airfoil’s thickness. The values decided on were 0.05”, 0.10”, and 0.15”.

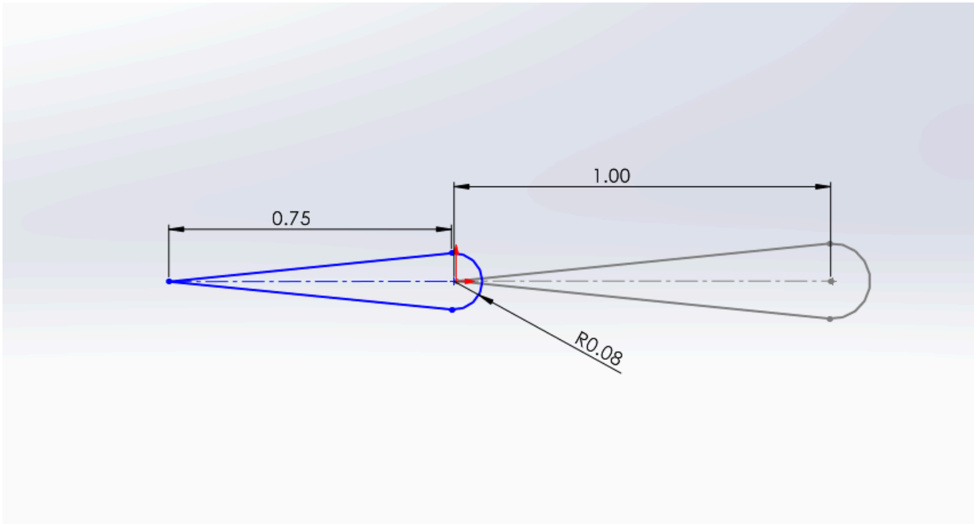

Figure 27. Wing Creation with Two Airfoils

To create the actual wing, another airfoil needed to be created that was displaced from the original. The second airfoil was sketched on a new plane that was displaced by 6" from the original airfoil making all the wings 6" long. Figure 27 details the sketch when creating the standard wing. The airfoil proportion denotes how big the second airfoil is compared to the original. Since the stander proportion is 0.75, the thickness and length of the second airfoil for the stander wing is 0.075" and 0.75" respectively. The airfoil displacement denotes how far the origins of the two airfoils are from each other. For the standard wing, the displacement is 1" as seen in Figure 27 above.

Appendix D: Professional Contact

Name: Thomas Miller, Ph. D

Title: Professor of Aerospace, Adjunct

Organization: Department of Aerospace College of Engineering University of Michigan

Phone: +1 (316) 213-3353

Email: millerth@umich.edu

Thomas Miller <millerth@umich.edu>   Thu, Aug 25, 8:11 AM
to Thomas, Christopher, me

Good Morning Mr. Qureshi,

Sounds like a fun project. There are many different parameters that go into gaining the results or data you are after. Broken down into their constituents, it's not too hard to figure out, it just takes some time.
Chris pointed out some good resources to get started. There are plenty of resources on the internet and other books that have data for different airfoils too.

Please email me some of your questions or we can set up a zoom call some time. Please let me know.

Best of luck and have fun!

--
Thomas Miller
University of Michigan
Department of Aerospace Engineering
1320 Beal Avenue
FXB Building
Ann Arbor, MI 48109-2140
316-213-3353 (Cell)

Figure 28. Profession Contact Email

Figure 28 is a screenshot of the email that Professor Thomas Miller sent back in response to the request for assistance on this project. He helped explain fundamental aerodynamic concepts and helped narrow the scope of this research.

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