

DESIGN AND MANUFACTURING OF A SURF FOIL

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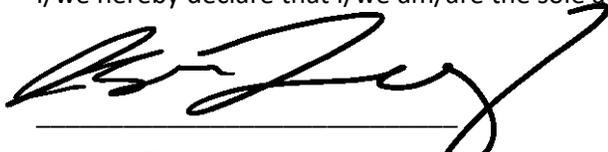
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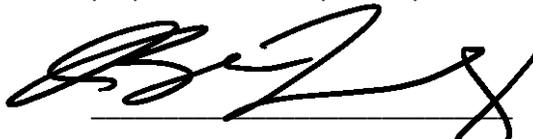


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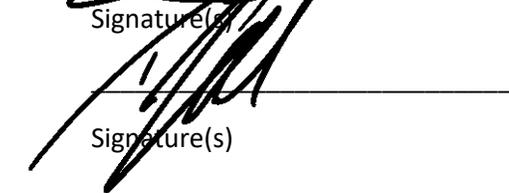
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Abstract

This project's objective is to analyze the physical concepts behind hydrofoils using the principles of aircraft design and aerodynamic wing theory. The team investigated the design concepts that go into the airfoils for planes and selected a suitable NACA airfoil to use in our project. We also researched the design decisions that go into the designs of the front and back wings; as well as, the fuselage. The team familiarized themselves with the technical nomenclature of the airplane industry and applied the mechanics in their design. Experts in carbon fibre architecture and avid surfers were consulted for their input in the design.

The team decided on a design with a dihedral angle for increased roll stability and a foil wing with a high aspect ratio. The NACA profile we chose was a very cambered profile, the NACA 6412. This allowed us the highest lift coefficient for the lowest attack angle.

The next section discusses the evolution of the design from the concept to the final manufacturing prototype. It contains the steps to manufacture the prototype from gluing the MDF board, CNC cutting the core, carbon fibre layup to the final surface finishing.

Finally, this report discusses the problems encountered during the manufacturing of the foil. It documents the errors we encountered like tool bit collision, collet collision, following error, tab thickness and epoxy surface layer. We conclude this report with the future work and improvements we could do with the manufacturing of the hydrofoil.

Acknowledgements

Throughout the duration of this project, several people played important roles crucial to the success and completion of this project.

Firstly, a special thanks to James Bartz for assisting in generating the G code required for the CNC router as well as for all the helpful tips and tricks he provided. Also, thank you to Steven Balog for setting aside time out of his schedule to help set up and supervise the CNC router. Without the help of both of these people, the CNC machined core would likely not have been completed in time and with such great results.

Secondly, a huge thank you to Rory Brown, Chris Townsend and Jason Brett for all their assistance in the wood and metal shops. Their familiarity with the machines, materials and their limitations were crucial in manufacturing components and solving unforeseen issues.

Finally, thank you to Casey Keulen, Johan Fourie and Greg King for providing their vast knowledge and experience to support/advise the design and manufacturing process. Having such knowledgeable project sponsors and advisors made the design/manufacturing process much more streamline and with minimal issues.

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Introduction

In response to Hydro Boarding Bros' request for proposal, the project team developed a prototype hydrofoil specifically designed for stand-up paddleboard users. It is optimized for foil pumping and has sufficient surface area to lift both the board and user out of the water. The objective of the project is to produce a hydrofoil that outperforms and challenges the status quo of the hydrofoil community.

The current status of hydrofoils designed for surfing or stand-up paddle boarding had no documentation of physics behind the design. So, our team tried to analyze the physical concepts behind the hydrofoil with the lenses of aircraft design. The team investigated the design concepts that go into the airfoils for planes and selected a suitable NACA airfoil to use in our project. We also researched the design decisions that go into the designs of the front and back wings; as well as, the fuselage. The team familiarized themselves with the technical nomenclature of the airplane industry and applied the mechanics in their design. Experts in carbon fibre architecture and avid surfers were consulted for their input in the design.

2 Detailed Description of the Current Status

Currently, all the required components for this project have been successfully manufactured. The manufactured components in the scope of this project include:

- Front wing
- Back wing
- Fuselage

Components that are purchased:

- Paddleboard (To be purchased)
- Mast (Received)
- Mast to board connection mount (Received)

Because the paddleboard has not been delivered yet, testing has been put on hold until the paddleboard is delivered. Therefore, the performance of this hydrofoil cannot be assessed at this time.

The next step is to test the hydrofoil in water once the paddleboard has been received to assess its performance while paddling and foil pumping.

The height of the wing is restricted by the height restriction of the CNC router used. The curvature of the front edge was minimized to make for easier carbon fiber layup.

Testing the foil is outside the scope of this project. If this project were to continue, the next stage would be to test the hydrofoil.

Current hydrofoils are not optimized for foil pumping, so our project was to design a stand-up paddleboard with the ability to be foil pumped. This allows the user to generate speed through paddling and foil pumping. The nearly 1m wingspan of the front wing allows enough surface area to provide enough lift for a stand-up paddleboard and a high enough aspect ratio so the drag of the foil is minimized.

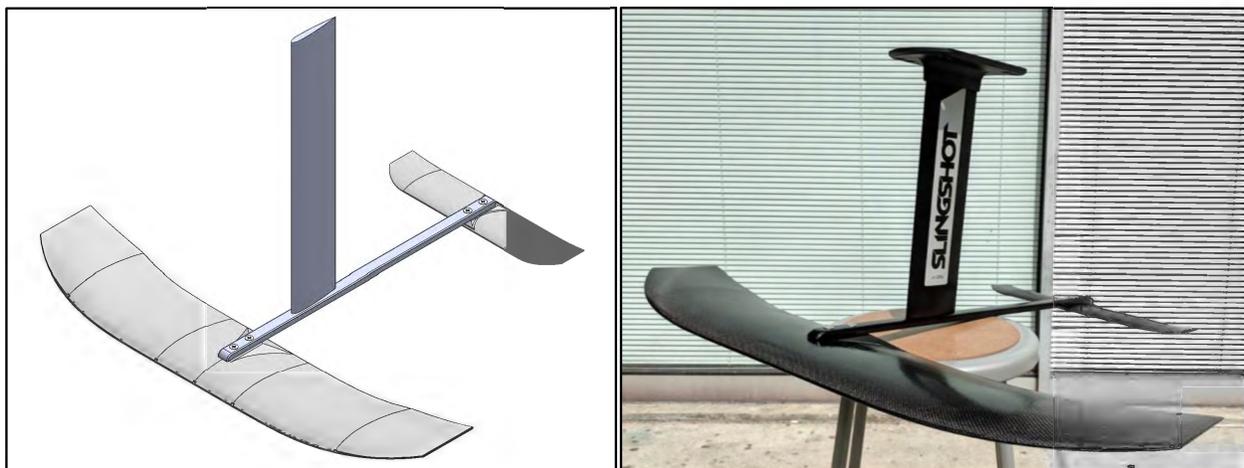


Figure 1: Final design compared to manufactured prototype

3 Theoretical Background

This chapter discusses the theory involved in the design and operation of hydrofoils. The theory behind adding a hydrofoil onto a stand-up paddleboard is to introduce another option of picking up speed while on the board through foil pumping. It also allows the board to have a higher operational velocity because as the board is lifted off the water there is less area for drag forces to hold the user back. The front wing of the foil is typically bigger than the back wing and provides most of the lift required to lift the user and the board. The back wing is used for balancing the pitching moment caused by the front wing. The shape of the wing is determined by the level of performance desired by the user and will be discussed later.

The concept of foil pumping greatly reduces the need for users to swim back out into the ocean after catching a wave. The user may pump the foil up and down to gain enough speed to turn around. As the user pumps the foil down there is a component of the lift that drives the foil forward and picks up speed.

Figure 2: Free Body Diagram of Pumping the Foil Downwards

Then as the user shifts their weight back, the foil a component of the lifts drives the foil up at the expenses of some speed. As the user repeats this cycle, the foil can gain more and more momentum to eventually lift the board out of the water.

Figure 3: Free Body Diagram of Pumping the Foil Upwards

3.1 Research and Nomenclature

To start off the project, the team researched the available hydrofoil boards out in the market and familiarized themselves with the nomenclature used in the hydrofoil community. In order to design the foil, we had to develop an understanding of what parts composed of the foil.

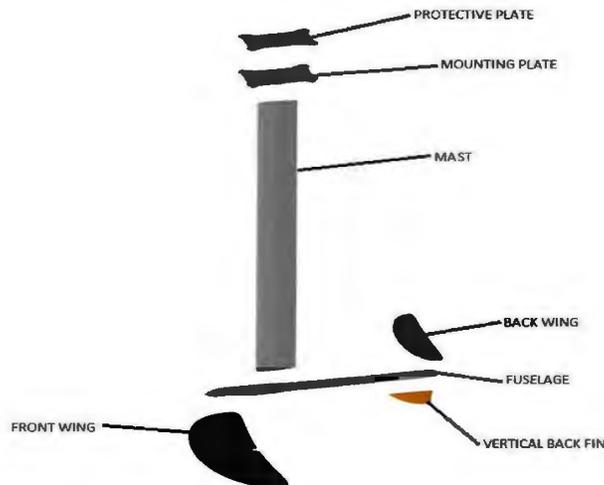


Figure 4: Parts of a Hydrofoil [1]

It was also necessary to standardize what terms meant for communication between teams so we compiled the common nomenclature into a report, which can be found in Appendix B. For further explanation of terms used in the report please reference Appendix B.

Some common and important nomenclature to note is the three rotational freedoms the board has in the water. It is roll, pitch and yaw as illustrated below.

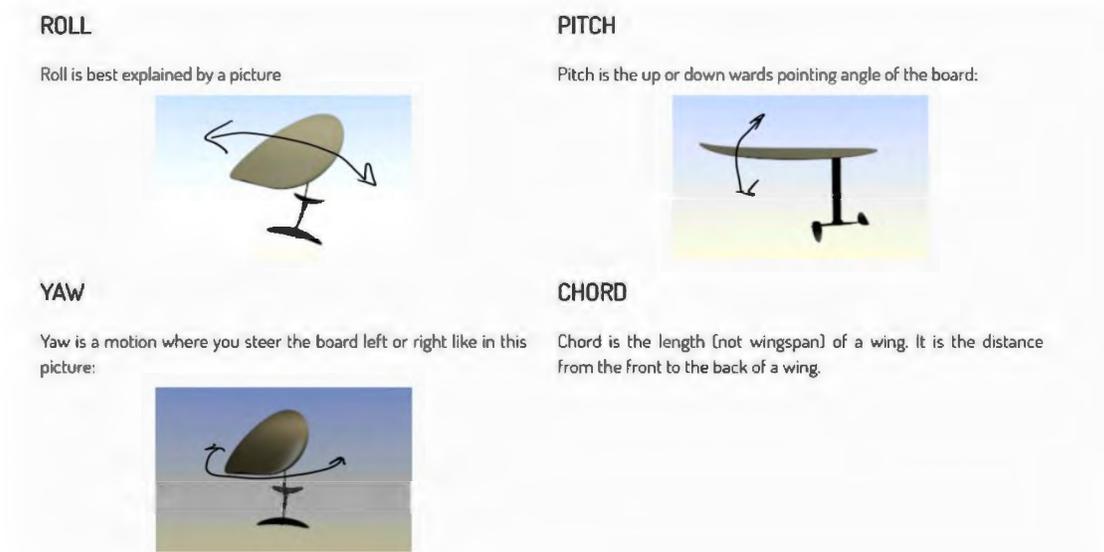
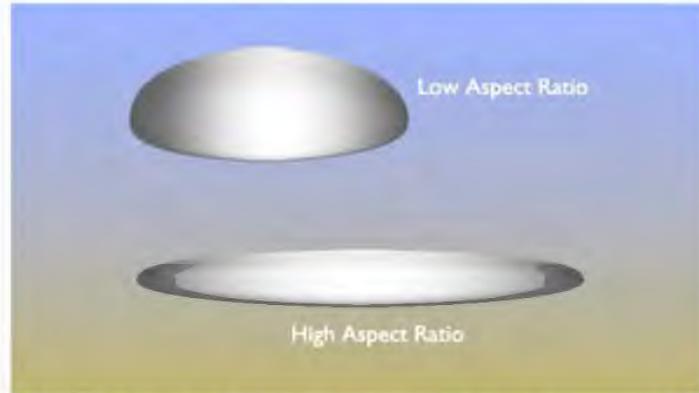


Figure 5: Three Rotational Freedoms of a Foil [2]

Another important aspect to the design of the wing is the aspect ratio, it determines if the surface area is contributing more to generating a lift force at the expense of taking on more drag.

ASPECT RATIO

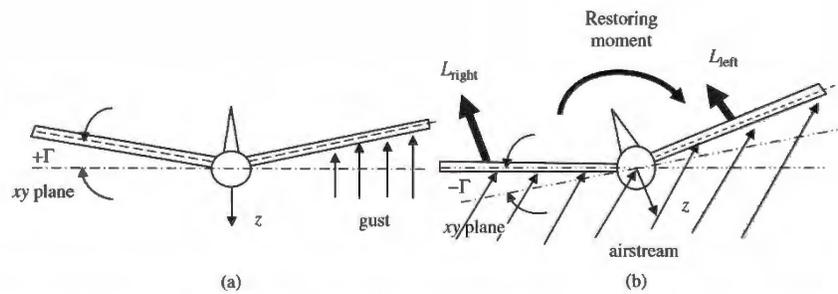
Aspect ratio is the ratio of the wingspan to the area of a wing. A wing with a short chord and long wingspan has a very high aspect ratio and vice versa.



Lets tackle the keel first, as it is probably the easiest one to design, but definitely not the easiest one to build. THE KEEL..

Figure 6: Aspect Ratio of a Foil Wing [2]

Finally, the last important terminology we will discuss is the effect of dihedral and anhedral angles of the wings of an aircraft. Designing a wing with a dihedral angle helps provide the plane with better roll stability. As the wings roll to the side, the area on one side is bigger than the area on the other and the difference provides a restoring moment to better stabilize the aircraft. [3] An anhedral angle does the opposite and accelerates the rolling motion instead.



In some references, it is called *dihedral stability*, since a wing dihedral angle provides

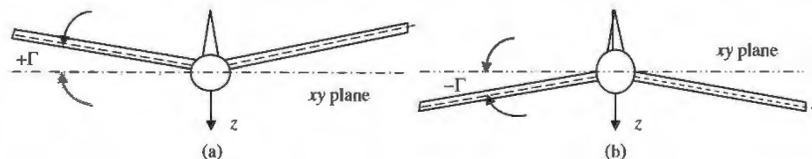


Figure 7: Dihedral (a) and Anhedral (b) Angles on an Aircraft [3]

Following the standardizing of common terminology between our team members we investigated hydro foils that were available in the market.

Common foils for people 160-190 lbs with intermediate skills:

Downwind SUP - Wing surface area 180-300 square inches

- GoFoil Maliko 200
- GoFoil Maliko 280
- Delta Mega surf
- Cloud 9 P27

Small waves - Wing surface area 140-230 square inches

- Cloud 9 P27
- Delta Surf
- Delta Mega surf
- GoFoil Iwa
- Lift 170
- Lift 200
- Naish Thrust Surf L
- Slingshot Fsurf H2
- Ride Engine Futura

Good waves - Wing surface area 120-170 square inches

- Cloud 9 S24
- GoFoil Kai
- Lift 150
- Liquid Force Impulse
- Naish Thrust Surf M
- Slingshot Fsurf H4
- Ride Engine Bat wing

Huge waves/tow in - up to 130 square inches surface area

- GoFoil Nalu
- Lift 110
- Delta Freeride
- Slingshot Fsurf H3

Figure 8: Foils Categorized for Preferred Usage [4]

Hydrofoil Specifications

Hydrofoil type	Surface area (Sq in)	Surface area (Sq cm)	Front wing span (in)	Front wing span (cm)
Cloud IX S24	175	1126	24"	61
Cloud IX P27	217	1406	27"	69
Delta Surf	194	1250	29"	746
Delta Mega Surf	232	1500	29"	746
Gofoil Kai	120	774	NA	NA
Gofoil Iwa	170	1097	NA	NA
Gofoil Maliko 200	200	1290	NA	NA
Gofoil Maliko 280	280	1806	NA	NA
Lift 150	150	968	24"	61
Lift 170	170	1097	25"	64
Lift 200	200	1290	26"	66
Liquid Force Impulse	175	1126	24"	61
Naish Thrust surf M	160	1032	24"	60
Naish Thrust surf L	191	1236	26"	66
Ride Engine Futura H2	*180	*1161	27"	69
Ride Engine Futura H4	*210	*1354	26"	66
Slingshot Fsurf H2	*180	*1161	27"	69
Slingshot Fsurf H4	*210	*1354	26"	66

This chart is the intellectual property of MACkite

Table 1: Physical Specifications of Several Foils [4]

Hydrofoil Lift Speed

Hydrofoil type	Lift begins (Board speed in MPH, 175lb rider)	Max speed (Board speed in MPH)	Foil stability 1-5 (5 being most stable)
Cloud IX S24	11	17	4
Cloud IX P27	7	14	5
Delta Surf	10	17	4
Delta Mega Surf	8	15	5
Gofoil Kai	11	17	4
Gofoil Iwa	9	15	4
Gofoil Maliko 200	8	14	5
Gofoil Maliko 280	6	12	6
Lift 150	11	20	4
Lift 170	10	18	4
Lift 200	8	16	5
Liquid Force impulse	11	17	4
Naish Thrust surf M	11	17	3
Naish Thrust surf L	10	18	4
Ride Engine Futura H2	8	16	4
Ride Engine Futura H4	8	14	4
Slingshot Fauri H2	8	16	4
Slingshot Fauri H4	8	14	4
<i>Extra low speed lift</i>			
<i>Low speed lift</i>			
<i>Moderate speed</i>			
<i>High speed</i>			

Table 2: Hydrofoil Lift Speed [4]

With a better idea of what the market currently is providing, the team also developed a stronger foundation to start making more informed design decisions. Because we are designing for a SUP foil at low velocity, we needed a wing with a lot more area than that of a typical surf foil. Using this data as a reference, we decided to assume the design will be for a user with a mass of 80kg (176lbs), a starting velocity of 3m/s (6.7mph) and a wing area of 1500 cm² (232.5 in²).

3.2 Design and Performance Parameters

Following the market research and investigating how the components of the hydrofoil worked, the team compared the design parameters required to the performance parameters. This project involved a lot of minimizing and maximizing desirable parameters because every design decision had trade-offs. We wrote a report on the correlation between these design parameters and performance parameters, and it is summarized in the chart below. A positive correlation means as we increase the design parameter, the affected performance parameters also increase. For example, increasing the fuselage length also increases the pitch stability and yaw stability. For more in depth discussion on these correlations refer to Appendix C.

Design Parameters	Affected Performance Parameters	Correlation
Fuselage Length	Pitch Stability	+
	Yaw Stability	+
Mast Length	Yaw Stability	-
	Roll Stability	-
	Max Operational Velocity	+
Front Wing Aspect Ratio (Top)	Max Operational Velocity	+
	Lift/Speed	-
	Lift to Drag Ratio	-
	Max Operational Weight of User	-
Front Wing Aspect Ratio (Side)	Lift to Drag Ratio	+
	Max Operational Weight of User	+
Back Wing Aspect Ratio (Top)	Pitch Stability	-
	Roll Stability	+
Back Wing Aspect Ratio (Side)	Pitch Stability	+
Vertical Fins	Yaw Stability	+
	Roll Stability	+
Anhedral Front Wing	Roll Stability	-
Anhedral Back Wing	Roll Stability	-
Total Surface Area Front	Max Operational Weight of User	+
	Max Operational Velocity	-
	Lift/Speed	+
	Lift to Drag Ratio	+
Total Surface Area Back	Max Operational Velocity	+
	Roll Stability	+
Material Density	Max Operational Weight of User	-
Angle of Attack	Lift to Drag Ratio	+
	Max Operational Weight of User	+
<p>Positive Correlation (+): Increase in Design Parameter results in Increase in Performance Parameter and vice versa</p> <p>Negative Correlation (-): Increase in Design Parameter results in Decrease in Performance Parameter and vice versa</p>		

Figure 9: Design and Performance Parameter Correlations

3.3 Selecting a NACA Profile

With the assumptions from the previous section we now had some values to solve for the lift coefficient required from the wing. Our approach to design was to determine the lift coefficient needed from the NACA profile with some assumptions and then select a suitable one from there. We would then use Xfoil software to verify our assumptions to finalize the profile.

NACA Profile

$$F_L = C_L \frac{\rho V^2}{2} A \quad \Rightarrow \quad C_L = \frac{2 F_L}{\rho V^2 A}$$

Assuming:

$m = 80 \text{ kg}$

$\rho = 997 \frac{\text{kg}}{\text{m}^3}$ (water)

$V \approx 3 \text{ m/s}$

$A = 0.15 \text{ m}^2$

$$Re \approx \frac{VL}{\nu} = \frac{3 \text{ m/s} (0.2 \text{ m})}{1.7937 \times 10^{-7} \text{ m}^2/\text{s}}$$

$$= 612,000$$

$$\therefore C_L = \frac{2(80 \text{ kg})(9.81)}{0.15 \text{ m}^2 (997 \frac{\text{kg}}{\text{m}^3})(3 \text{ m/s})^2} = \boxed{1.17}$$

with our assumptions we want a lift coefficient of $C_L = 1.2$.

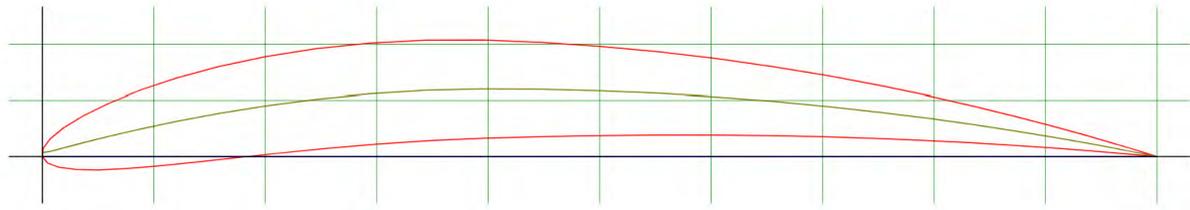
Choose: NACA 6409 9% or NACA 6412 at $\alpha \approx 5^\circ$.

Figure 10: Lift Coefficient Hand Calculation

From our hand calculations we calculated a required C_L of 1.17 at an $\alpha \sim 5^\circ$. This result narrowed the NACA profile options to NACA6409 9% (n6409-il) and NACA 6412 (naca6412-il).

NACA6409 9% (n6409-il)

NACA6409 9% - NACA 6409



Cl v Alpha

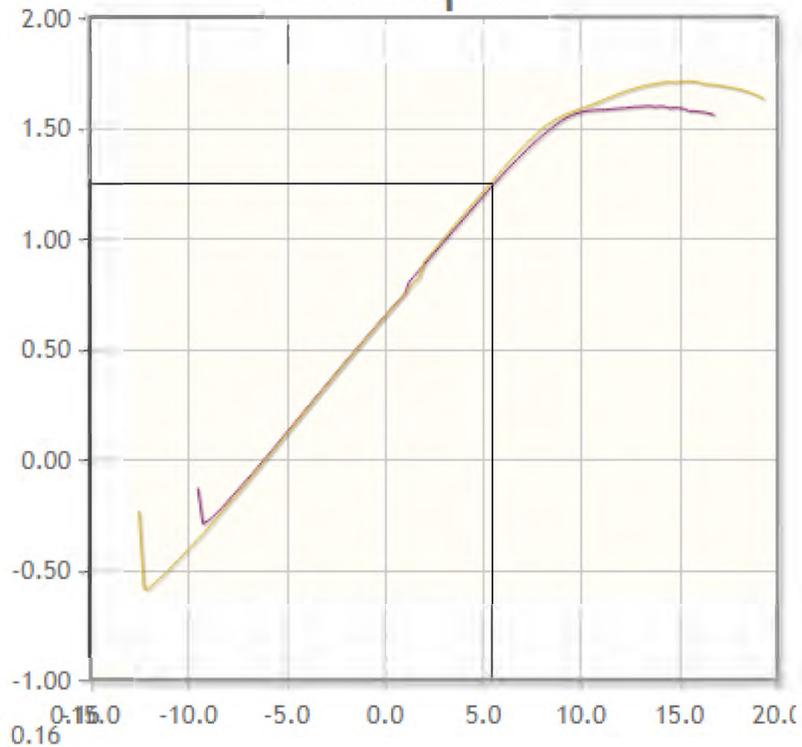


Figure 11: NACA 6409 9% Coefficient of Lift to Attack Angle [5]

The graph represents the coefficients of lift for the NACA6409 9% at Reynold's numbers of 500 ,000 (purple line) and 1,000,000 (yellow line). For our Reynold's Number of 612,000 we are looking at in between those two curves.

NACA 6412 (naca6412-il)

NACA 6412 - NACA 6412 airfoil

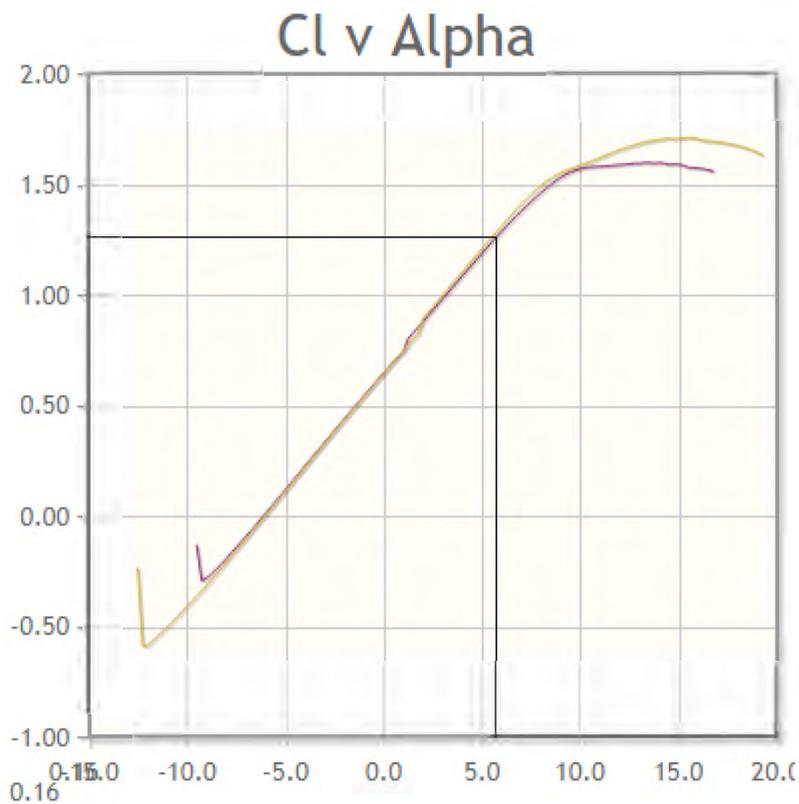
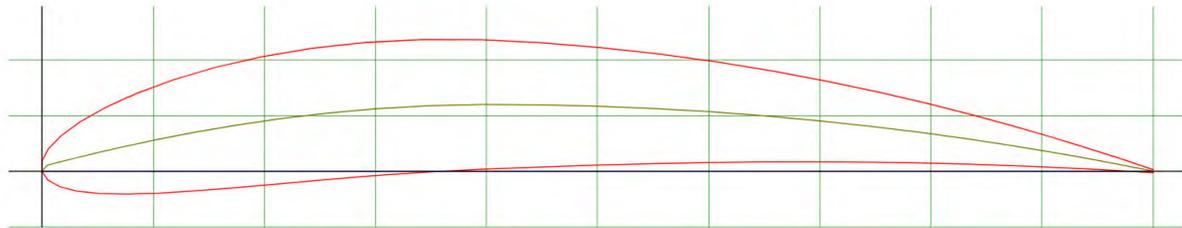


Figure 12: NACA 6412 Coefficient of Lift to Attack Angle [6]

Because both profiles yielded very similar results, we decided to move forward with the NACA 6412 for the thickness of the wing. A thicker wing would make manufacturing easier down the line and more structurally sound.

NACA 6412 (naca6412-il)
 NACA 6412 - NACA 6412 airfoil

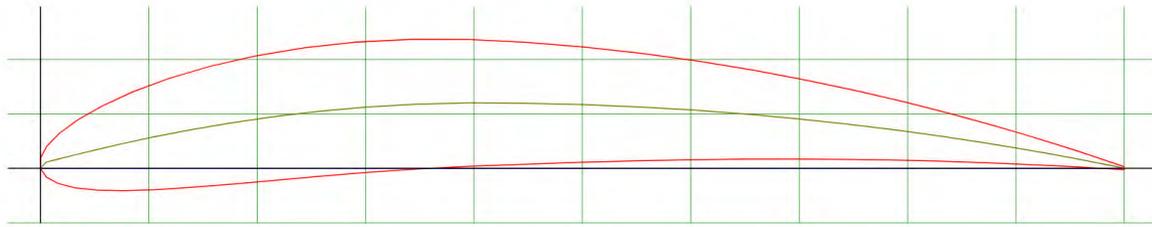


Figure 13 NACA 6412 [6]

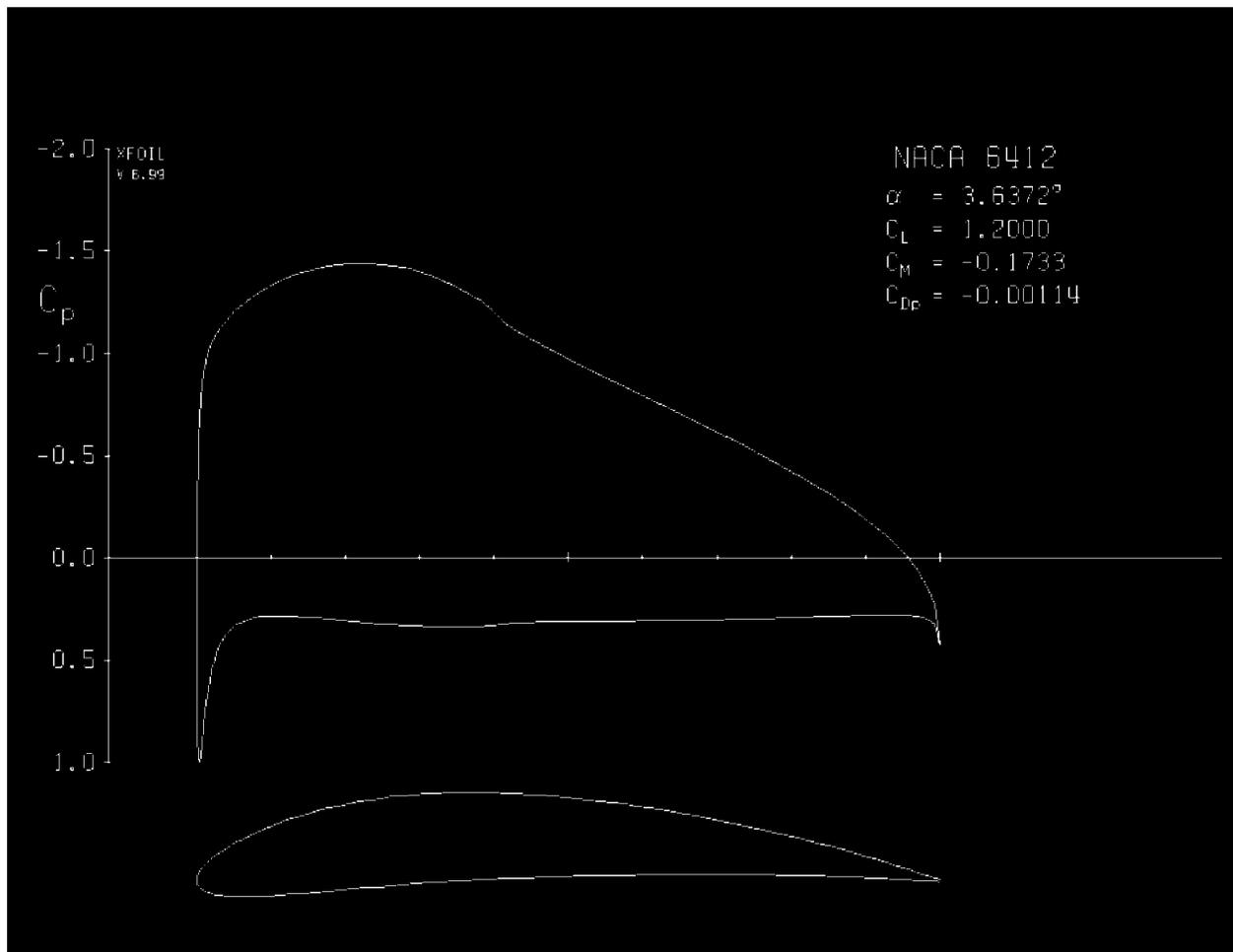


Figure 14: Required Coefficient of Lift

Xfoil is a software developed by MIT to simulate different NACA profiles and combines the extensive data of different foils and fluid mechanics. We verified our assumptions with this software and simulated the pressure distribution of the NACA 6412 we chose. From this we found the foil must be

angled at a $\alpha=3.6^\circ$ in order to achieve the lift coefficient required. This is a very minute angle that could easily be achieved from the foil pumping motion and was acceptable for our application.

3.4 Fuselage and Rear Wing Design

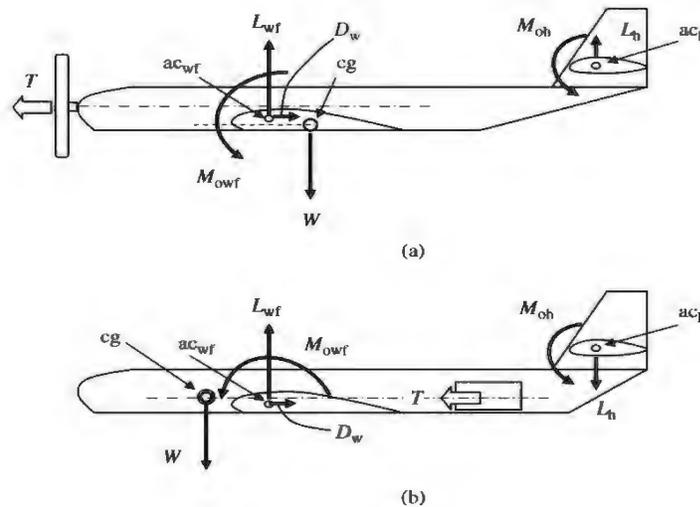


Figure 15: Lift forces of the Back Wing for Different Centres of Gravity

The function of the back wing is typically used to balance out the pitching moment of the lifting force provided by the front wing. [3] The direction of lift the back wing provides is dependent on the location of the centre of gravity. The surfer or stand-up paddleboarder typically stands near the rear of the wing and has the freedom to adjust the location of the centre of gravity. For the purposes of design, we will assume the centre of gravity will be over the centre of the mast. We made a design decision to halve the surface area of the front wing for the back wing. In order to balance the moments of the forces the length of the back wing must then be twice the length of the front wing from the centre of the mast. From our market research and this knowledge, we decided to design the fuselage to be 60cm with the back wing 40cm from the mast. The back wing will also be providing lift in the positive y direction to balance the moments.

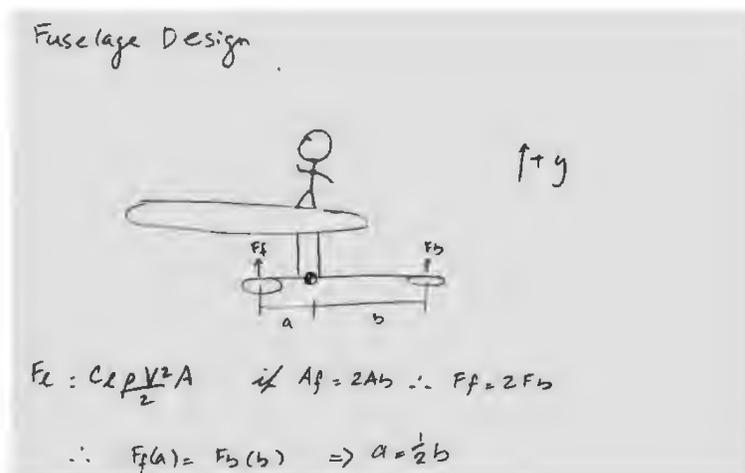


Figure 16: Diagram of the Centre of Mass of a Foil

4 Description of the Project Activity and Equipment

This chapter discusses the evolution of the design from the concepts we discussed in the design review (Appendix D) all the way to manufacturing. We will discuss the equipment and parts used to develop a hydrofoil and the manufacturing revisions we had to make to solve the problems we encountered in our initial design. It also outlines the steps to manufacture a hydrofoil for the future reference of anyone who would like to do so. It will also present the final prototype drawings. Testing and verifying the prototype is outside the scope of this project.

4.1 Concepts

4.1.1 Concept #1: Anhedral Design

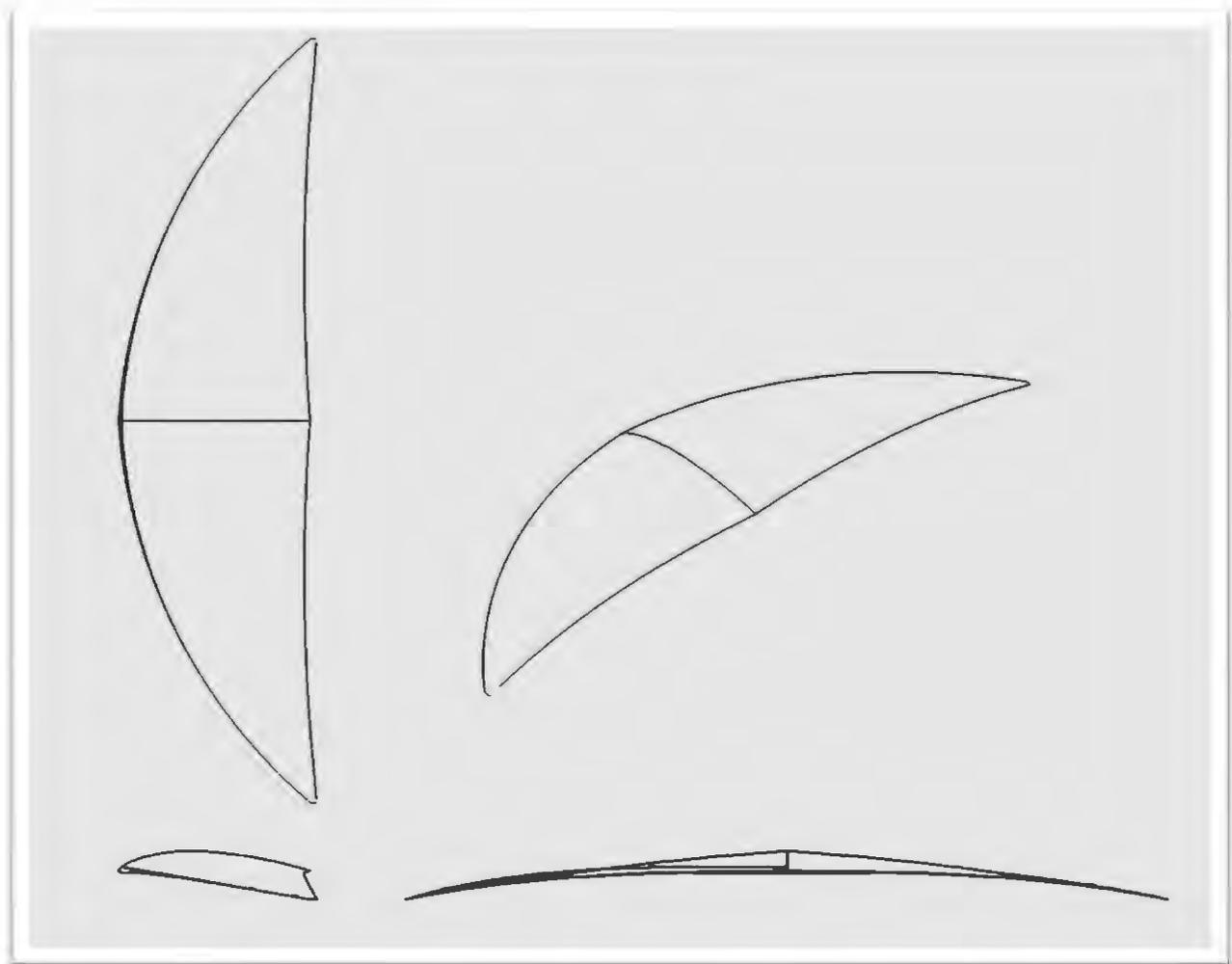


Figure 17: Anhedral wing design

The anhedral shape in this design helps with maneuverability. This design makes the wing less stable. It will take less effort to roll the foil during use. The anhedral wing design is the most common on current commercial surfing hydrofoils.

4.1.2 Concept #2: Flat design

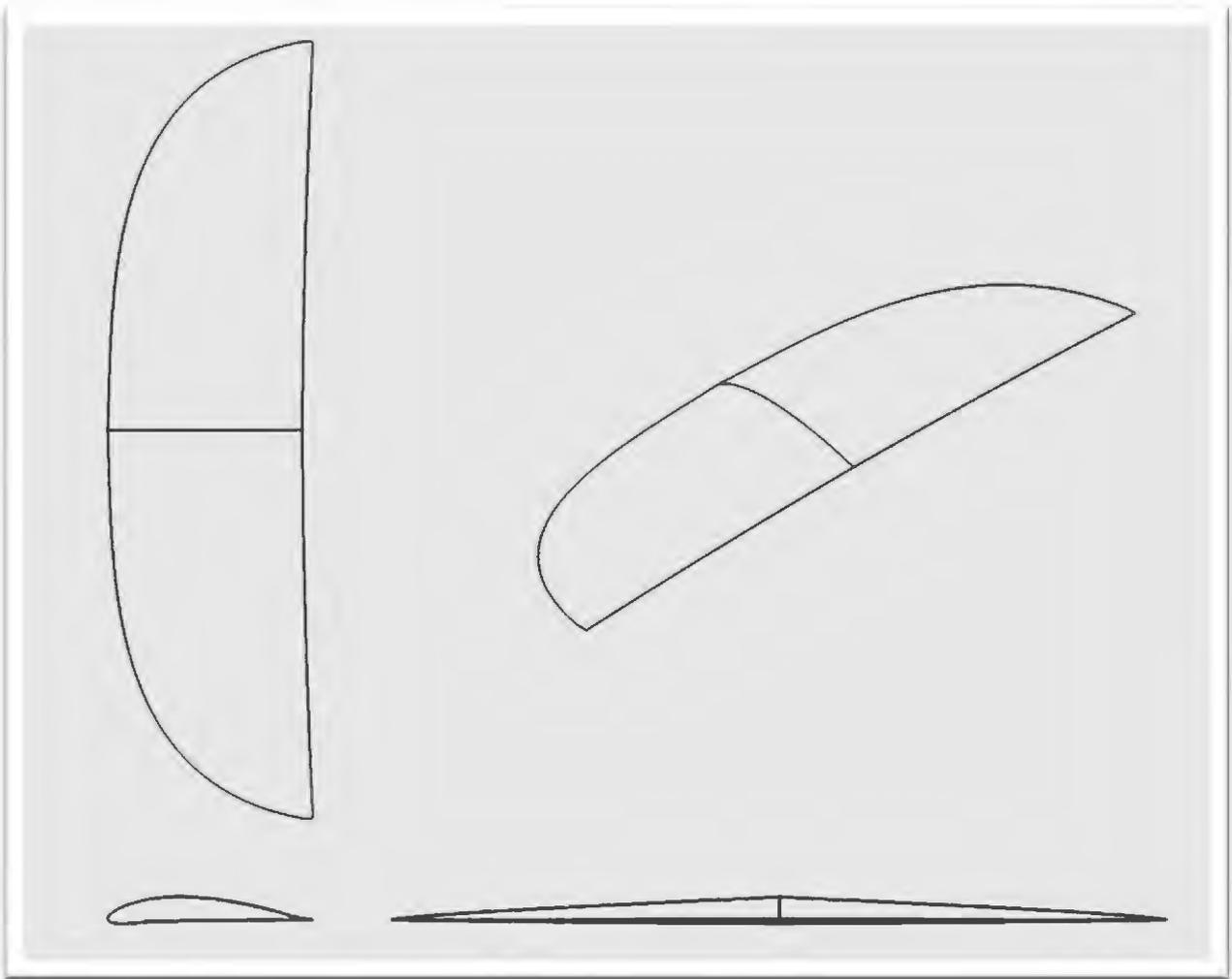


Figure 18: Flat Wing Design

The flat design is very common for back wings. This design has a neutral performance. This design is common for most back wings, as the stability response of a back wing should be neutral.

4.1.3 Concept #3: Dihedral Design

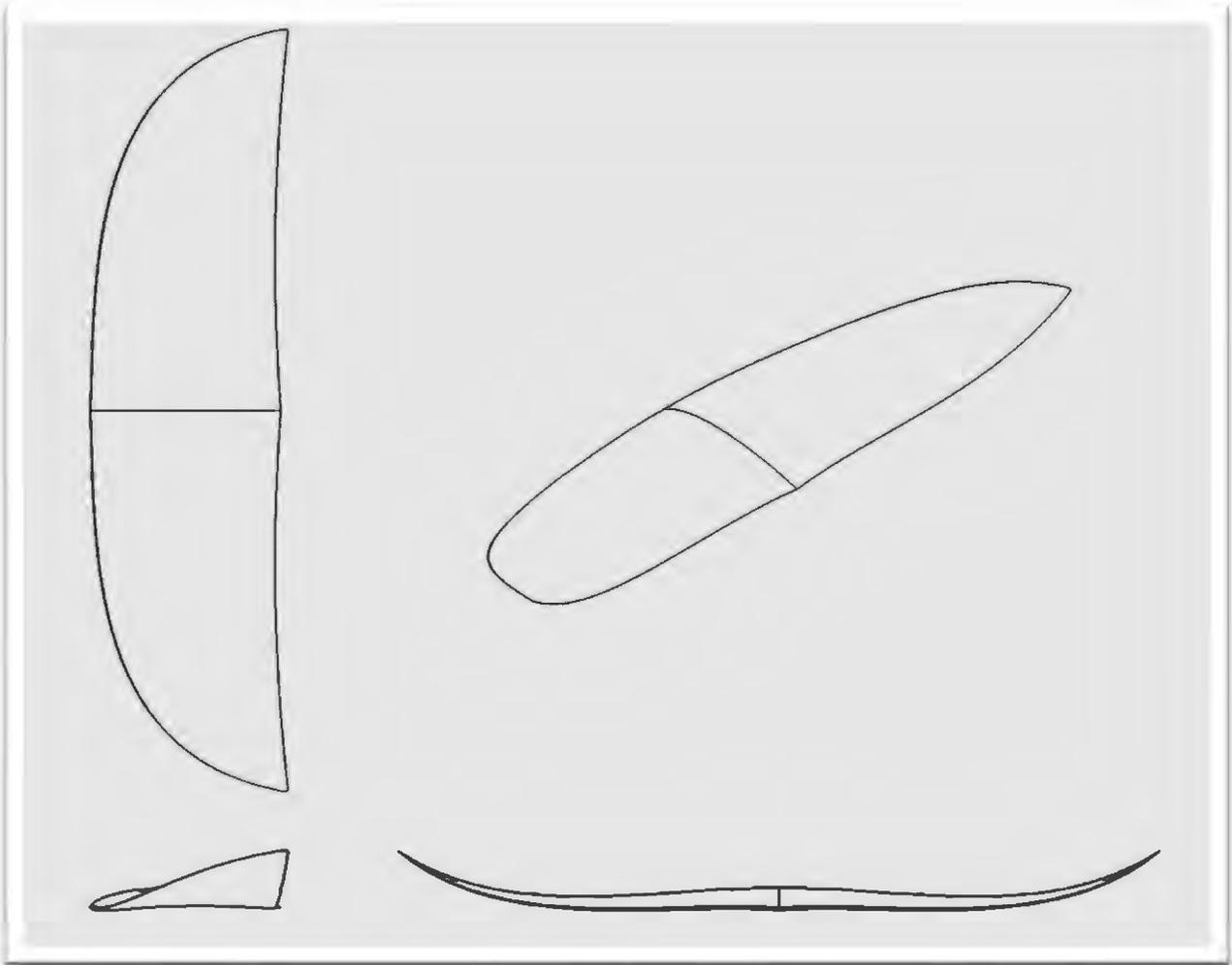


Figure 19: Dihedral wing design

This design increases stability. It will take more effort to roll the foil during use. Increasing stability would be desired for stand-up paddleboards.

4.2 Concept Selection

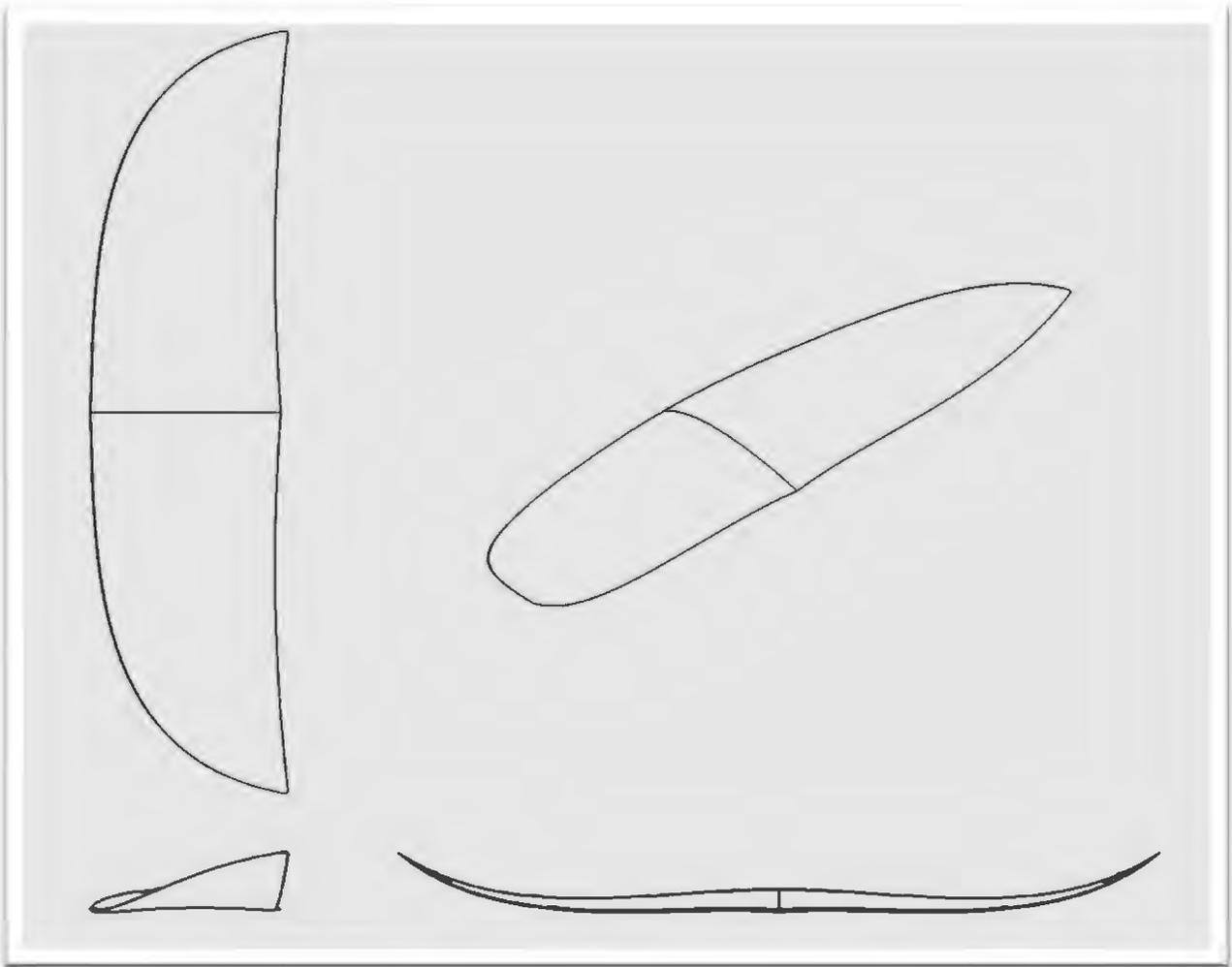


Figure 20: Selected concept - Dihedral wing shape

The dihedral shape was selected to help with stability, because it is difficult to initially gain speed with the combination of a paddle and the pumping motion. Having roll stability eases the process of pumping. A large surface area was chosen to increase lift at low velocities and a large wingspan of 80cm was selected to aid with foil pumping

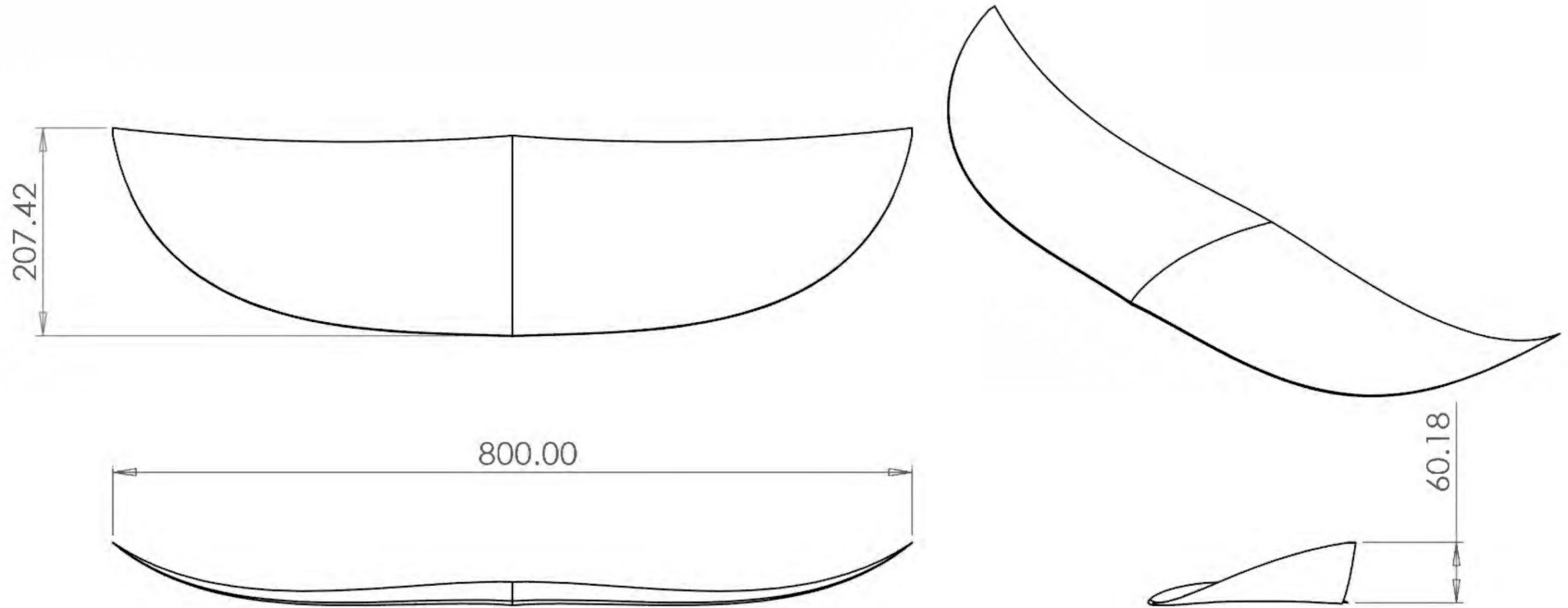
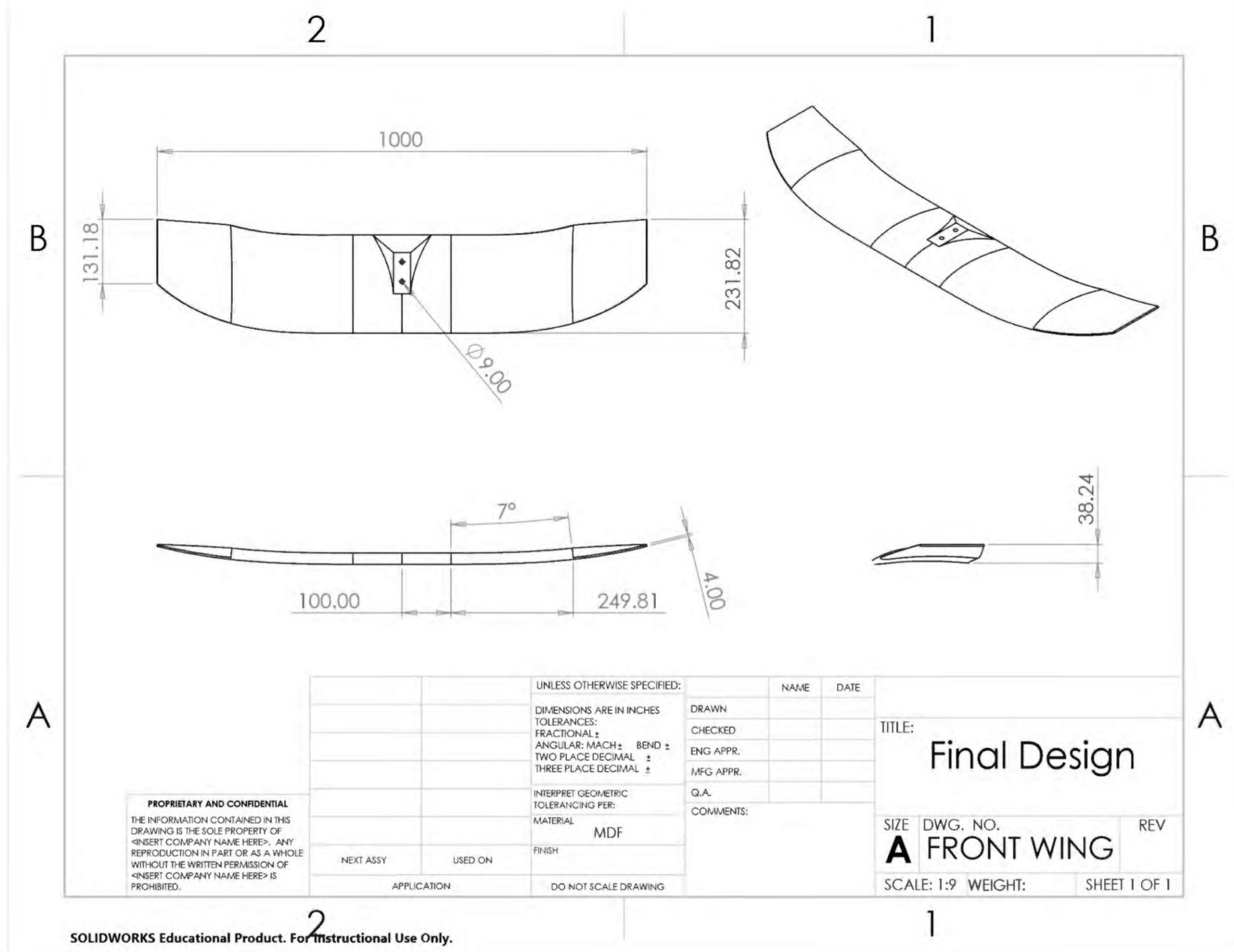


Figure 21: Initial Front Wing Concept

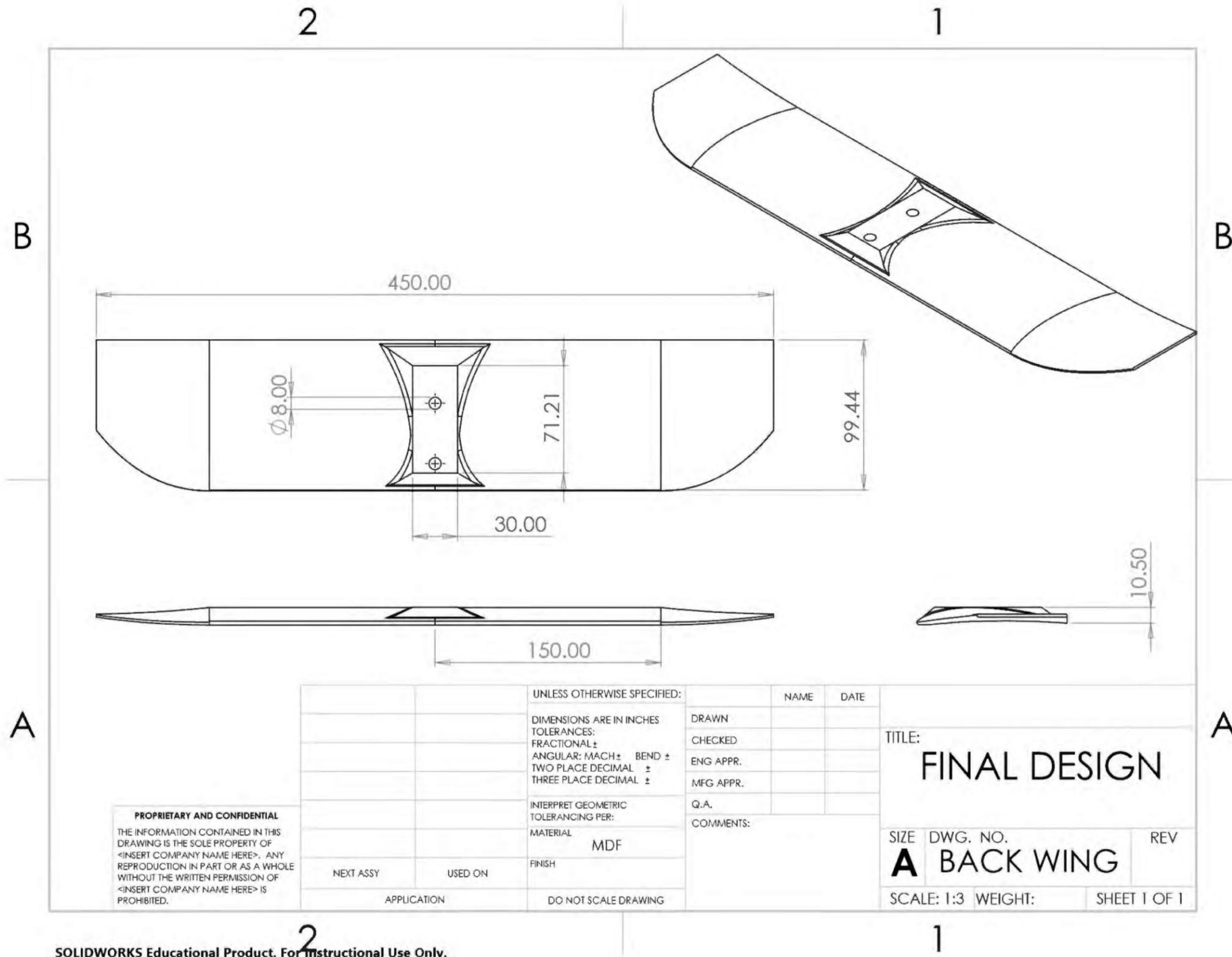
4.3 Evolution of design

The initial design of the front wing had an 80cm wingspan. The wingspan was increased to 100cm because it is believed that having a higher aspect ratio helps with foil pumping. To reduce pinching of the carbon fiber on the front edge of the wing, the curvature of the front edge was reduced. The initial overall height of the front wing was 2". Due to the height restrictions of the cutting area of the tool bit, the overall height and dihedral angle of the wing had to be reduced to under 2". The final height of the front wing is 1.6". Flat surfaces were added because of the decision to make the fuselage out of rectangular bar stock. Having a flat interface makes the manufacturing and assembly of the fuselage easier.



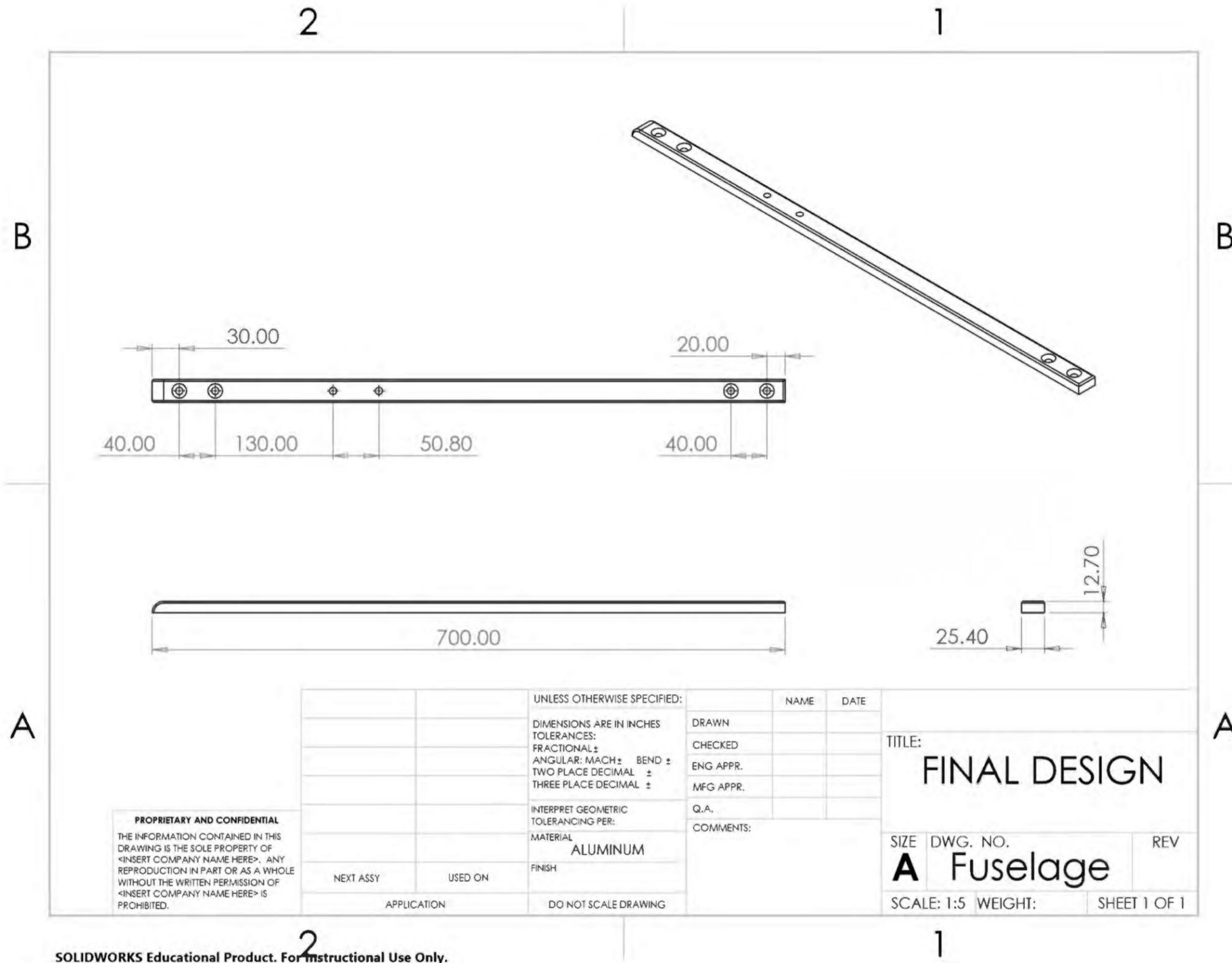
SOLIDWORKS Educational Product. For Instructional Use Only.

Figure 22: Final Front Wing Design



SOLIDWORKS Educational Product. For Instructional Use Only.

Figure 23: Final Rear Wing Design



SOLIDWORKS Educational Product. For Instructional Use Only.

Figure 24: Final Fuselage Design

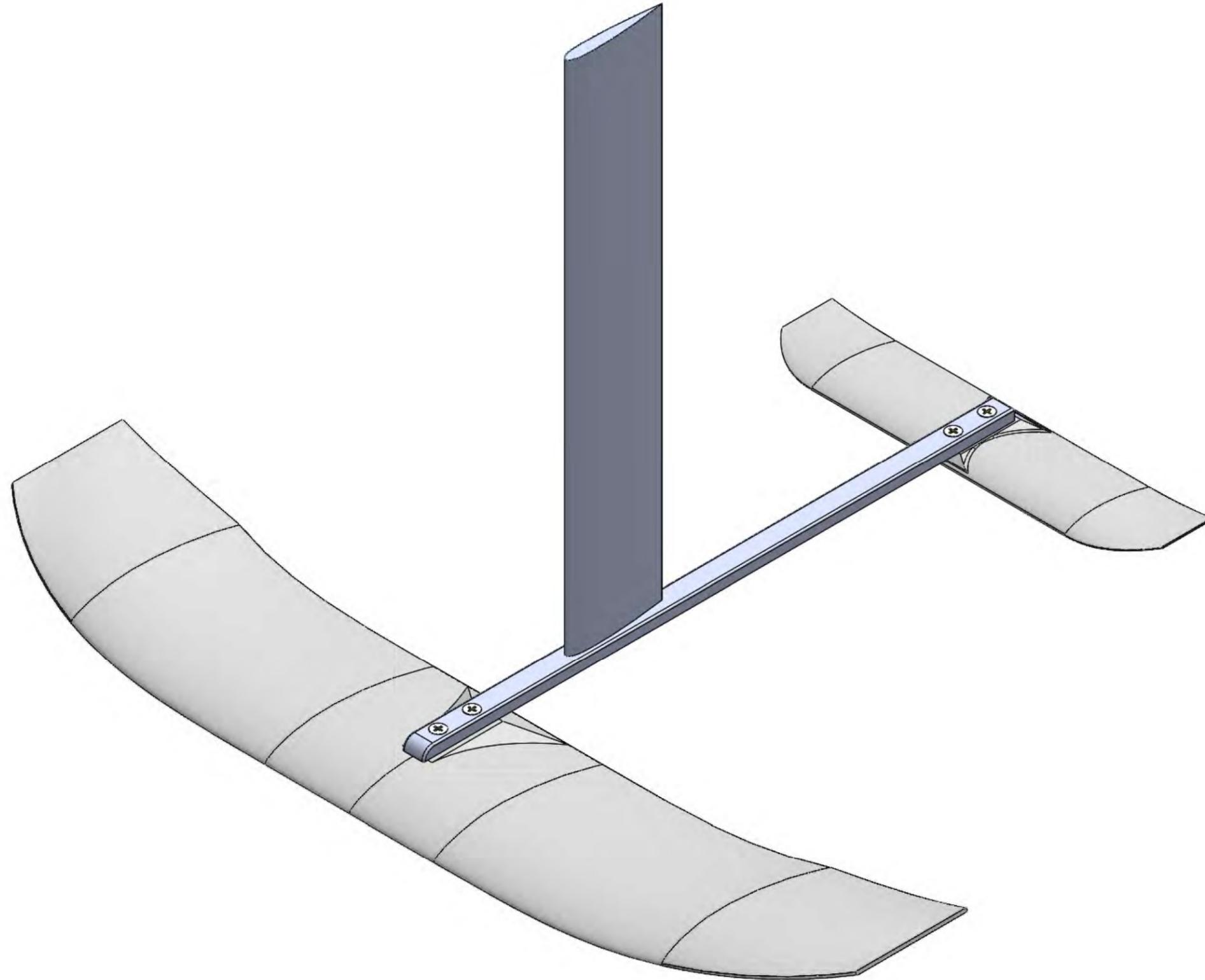


Figure 25: Complete Hydrofoil SolidWorks Assembly

4.4 Components and Materials

Number of components	Component	Material	Purchased or Manufactured
1	Front Wing	Carbon Fiber/MDF	Manufactured
1	Back Wing	Carbon Fiber/MDF	Manufactured
1	Fuselage	Aluminum	Manufactured
1	Mast	Aluminum	Purchased
1	Baseplate	Aluminum	Purchased
1	Paddleboard	Undetermined	To be purchased
12	M8 screws	Stainless steel	Purchased

Table 3: Components and Materials

4.5 Manufacturing

4.5.1 Manufacturing Hydrofoil

Step 1: Create MDF stock piece



Figure 26: MDF Stock piece

For the stock piece of the front wing, 3 sheets of $\frac{3}{4}$ " MDF were combined using wood glue. The block was abrasively sanded down to 2". The dimensions of the stock piece for the front wing are 45"x12"x2". The back wing was designed to only use 1 sheet of $\frac{3}{4}$ " MDF. The dimensions of the stock piece for the back wing are 7"x22"x $\frac{3}{4}$ ".

Step 2: CNC MDF core



Figure 27: CNC Core process

The top side of the wing is CNC machined from the MDF stock piece. The piece is then flipped to CNC the bottom side. The front wing core took approximately 3 hours to CNC. The back wing took approximately 30min to CNC.

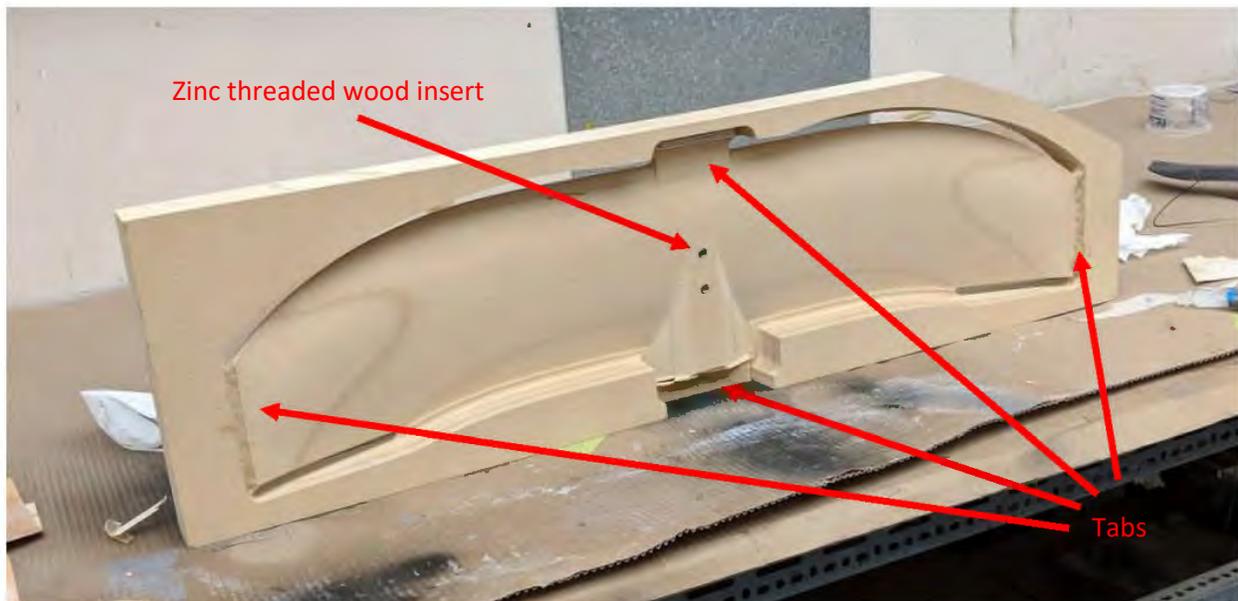


Figure 28: Finished CNC wing core

Zinc threaded inserts were added after the CNC process to help connect the wing to the fuselage. Tabs were implemented to help locate the part when flipped for the 2nd CNC process

Step 3: Cut and sand down tabs



Figure 29: Wing core removed from stock piece

The core of the wing is removed from the stock piece by sawing the tabs off. The tabs and the surface of the wing core are sanded down to give a smooth finish in preparation for layup.

Step 4: Carbon fiber layup

The MDF core is coated with epoxy and laid up with 2 layers of carbon fiber. The wing is placed in a vacuum bag to ensure the carbon fiber conforms to the desired shape of the core. The threaded inserts were covered with tape to ensure no epoxy interferes with the threads

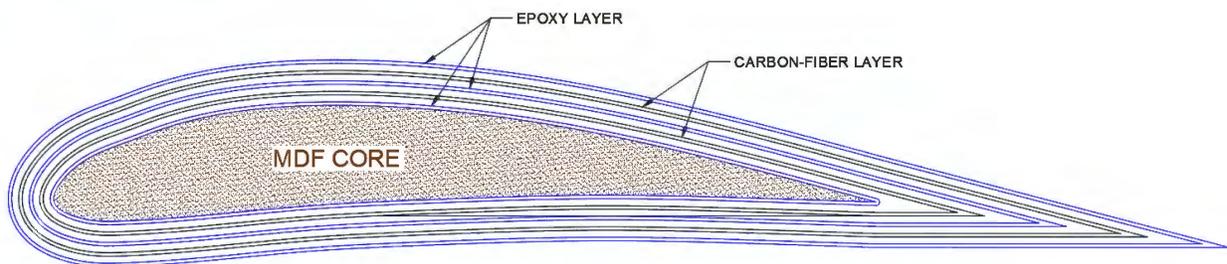


Figure 30: Layers of CF layup process



Figure 31: Carbon fiber layup process



Figure 32: Vacuum bagging wing



Figure 33: Wing after vacuum bagging

Step 5: Remove excess material



Figure 34: Hydrofoil after excess material removed

Using a die grinder, all the excess material of carbon fiber is removed from the wing. The creases and edges in the carbon fiber are sanded down by hand. The holes where the threads are located are drilled out.

Step 6: Exterior epoxy coating



Figure 35: Exterior coating of epoxy added

After the wing is removed from the vacuum bag the surface is rough because of the carbon fiber weave. An exterior coating of epoxy is added to create a smooth finish. A clear coat spray is added to protect the wing from UV light after the epoxy is sanded down.

4.5.2 Manufacturing Fuselage



Figure 36: Drilled and countersunk connection holes

The fuselage was created from a 1" x ½" aluminum bar stock. Figure 36: Drilled and countersunk connection holes. The stock was cut to 70cm. The holes for M8 screws were drilled out and countersunk.



Figure 37: Powder coating process

The fuselage was powder coated black.



Figure 38: Powder coated fuselage

4.6 Finished Prototype



Figure 39: Assembled Hydrofoil design

The final prototype of the design was assembled will need to be tested.

5 Discussion of Results

This section will consist of the following two subsections:

- Manufacturing Difficulties
- Final Prototype

There were several manufacturing difficulties during the production of the final prototypes of each component. This subsection will outline the major difficulties and issues encountered during the manufacturing process and the solutions/mitigations strategies implemented to solve these issues.

The result of the final prototype will then be discussed, addressing any defects or flaws that may have occurred during the manufacturing phase.

5.1 Manufacturing Difficulties

This section will outline the manufacturing difficulties encountered during the prototype production phase of this project. There were several unforeseen issues and complications that had not been considered which resulted in some defects/flaws in our manufactured results. The following sections will outline the major manufacturing issues faced when machining the required components and the solutions to these problems.

5.1.1 Tool-bit Interference/Collision with Stock Material

The depth of cut required for the CNC router to cut the wing and to accommodate its overall height due to the dihedral angle produced a conflict with the tool bit and the walls of the stock material. Because the cutting length of the tool bit (and most generic tool bits) was approximately 1.75 inches and the depth of cut into the stock material was over 2 inches, the non-cutting portion of the tool bit was contacting the walls of the stock material and caused the CNC router to stop. The bit would burn into the wood and deflect the cutting bit into the wing and cause a error in the machine.

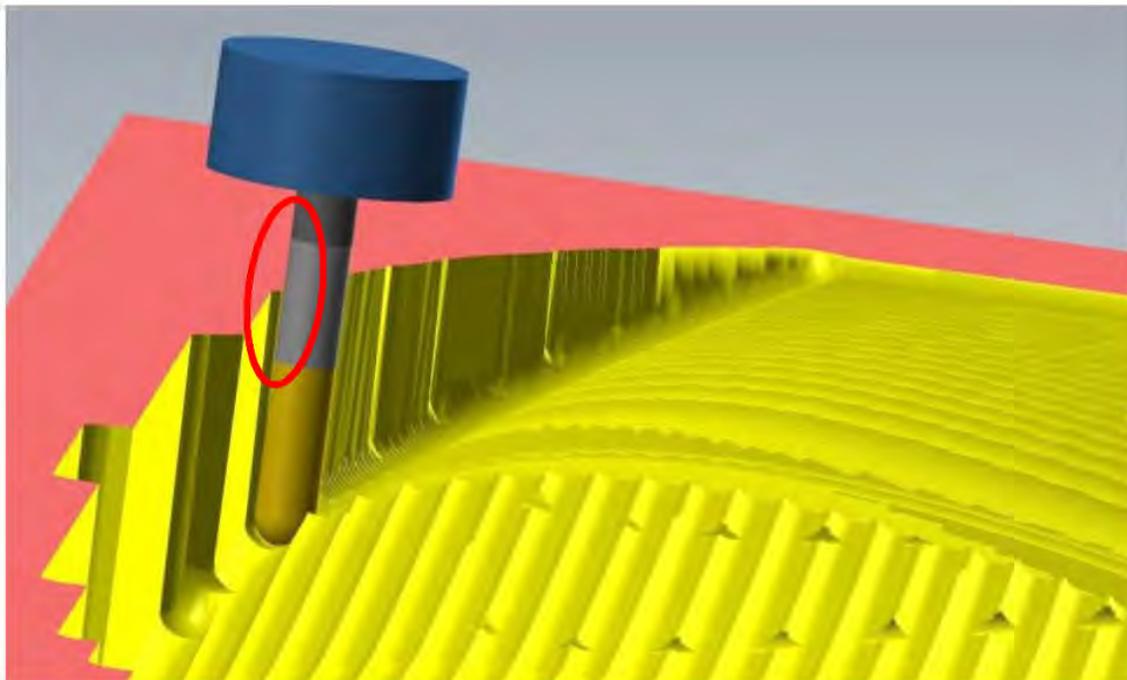


Figure 40: Tool bit collision

Two solutions were implemented to solve this issue. First, the total height needed to accommodate the dihedral angle was decreased; The wingspan remained the same, but the dihedral angle was reduced to decrease the overall height of the wing and consequently, decrease the required depth of cut into the stock material.

Additionally, clearance cuts were added first in the G code to cut away the portion of the walls that were coming into contact with the non-cutting length of the tool bit.

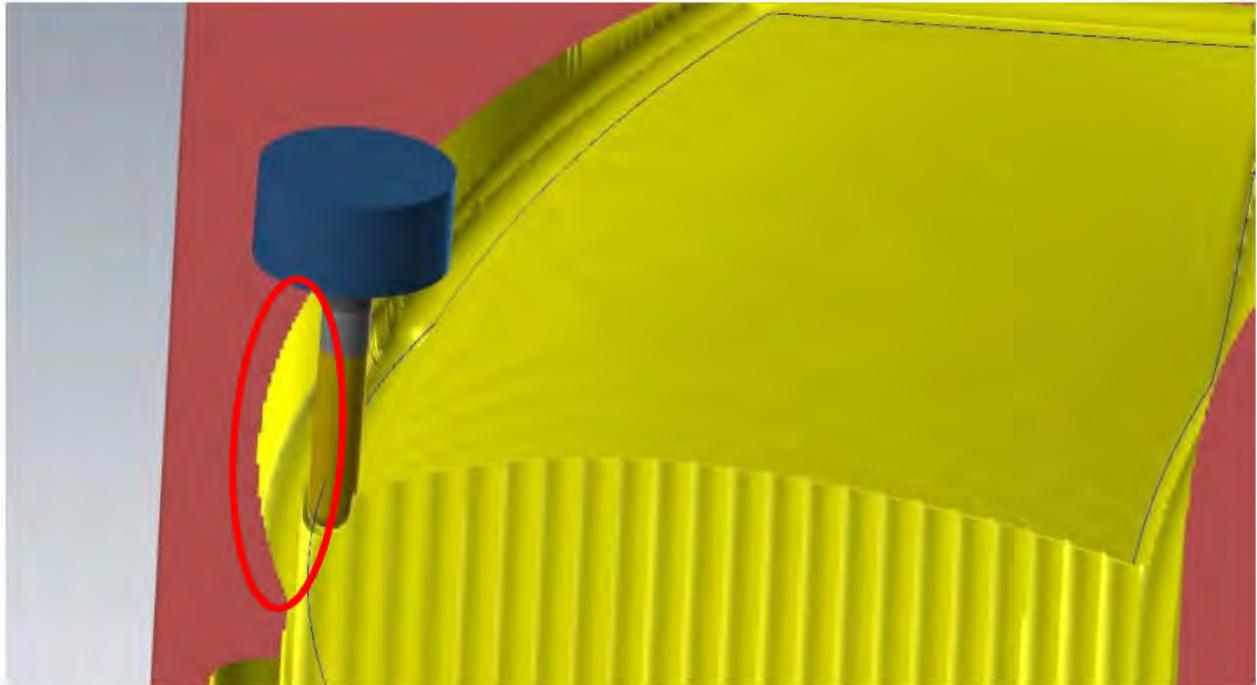


Figure 41: Clearance Cut

Both of the above solutions successfully solved this issue; however, with the addition of the clearance cuts, decreasing the overall height of the wing was not necessary. Therefore, incorporating clearance cuts will remove the overall height restriction of the wing allowing for most drastic and aggressive dihedral/anhdral angles.

5.1.2 Collet Collision with Top of Stock Material

Despite measuring the tool bit and entering its parameters into Mastercam to avoid this issue, the required depth of cut into the stock material also caused the collet holding the tool bit to come into contact with the top of the stock material. The rapid rotation of the collet while pushing down on the stock material caused slight burning and resulted in the CNC router to stop.

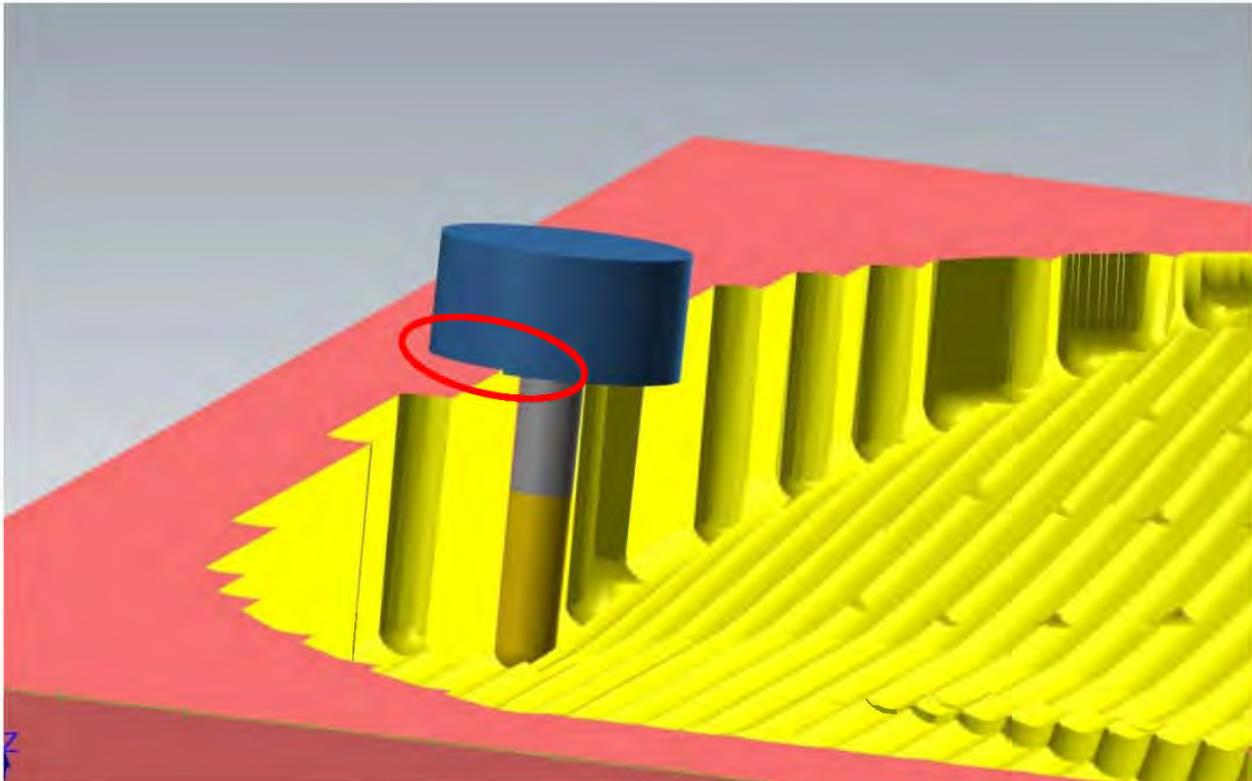


Figure 42: Collet Collision

This was likely due to the tool bit being installed too far into the collet. However, because there was minimal clearance between the collet and top of the stock material even when the tool bit was installed at its maximum length, the solution was to use a longer tool bit which successfully solved this issue.

5.1.3 Tab Thickness & Placement

Tabs are necessary because the workpiece was machined on the CNC router from both the top and bottom. The cuts from the second side would meet with the first, completely separating the workpiece from the stock material. Without tabs, the workpiece would be able to deflect and eventually completely detach from the stock piece when machining from the second side.

The major considerations regarding tabs are their placement and thicknesses; The workpiece needs to be supported on all sides that will separate from the stock material. For each wing, tabs were incorporated on the front, back and both wing tips to minimize deflection while machining. However, tab thickness for the material that is being machined must also be considered; The initial tabs on the wing tips were too thin and one broke during machining. This unfixed end allowed that side of the wing to deflect while being machined, producing a slightly asymmetrical and altered result from the other side.

5.1.4 CNC Router “Following Error”

While running the G code on the CNC router, occasionally the machine would stop due to a “following error.” This occurs when the CNC router is transitioning from feed speed (G01) to the rapid/traverse motion (G00) and is likely due to the older machine not begin able to move or accelerate as fast as it needs to as a result of insufficient motor torque, misaligned parts or excess friction.

The solution to this was to change all the rapid/traverse motions (G00) to feed speeds (G01) as the feed speeds have a much lower velocity. However, this did increase the overall time required to cut the piece on the CNC router.

5.1.5 Carbon-fiber Folding During Layup Process

Initial testing of the layup process was done with a soft, absorbent peel-ply cloth that formed and acted like a soft cloth. Folds that formed on the outer layers of the breather cloth and peel-ply during the vacuum bagging process did not propagate through to the carbon-fiber layer. However, due to lack of resources, a different peel-ply material was used on the final front wing. This peel-ply material was much harder, less absorbent and formed/acted like tissue paper rather than cloth.

This harder and less porous peel-ply material caused the folds that formed on the breather cloth and peel-ply during the vacuum bagging process to propagate through to carbon-fiber layer.



Figure 43: Folding on carbon-fiber layer

For future layups, it is recommended to use softer, higher quality and more absorbent peel-ply cloth to produce better results with minimal chance of folds propagating through to the carbon-fiber layer.

5.1.6 Non-uniform Epoxy Layer

Several different methods of applying epoxy layers to the carbon-fiber were tested and each had their respective issues associated with them. First, the epoxy was applied using a small paint roller. This produces a very uneven coat, leaving several small pits/bubbles on the carbon-fiber that were not coated in epoxy. Additionally, fibers from the roller came off and were infused into the epoxy layer coating the carbon-fiber.

A paintbrush was then used instead of the roller and produced an even and consistent coating on the carbon-fiber surface. However, fiber strands from the paintbrush also came off and was embedded in the layer of epoxy. To minimize this, tape was used to remove any loose strands from the brush.

Once the epoxy dried, there were a few spots of significant pitting in which the epoxy did not coat the carbon-fiber. These spots were noted during the epoxy application process because the epoxy would not stay coated to these areas despite continued application of epoxy. This could have been due to the presence of dirt or oil on the surface of the carbon-fiber before the epoxy coating. Further tests of epoxy applications showed that cleaning the surface of the carbon-fiber with isopropyl alcohol to remove any dirt or oils was successful in eliminating these problematic areas.



Figure 44: Non-uniform Epoxy Layer

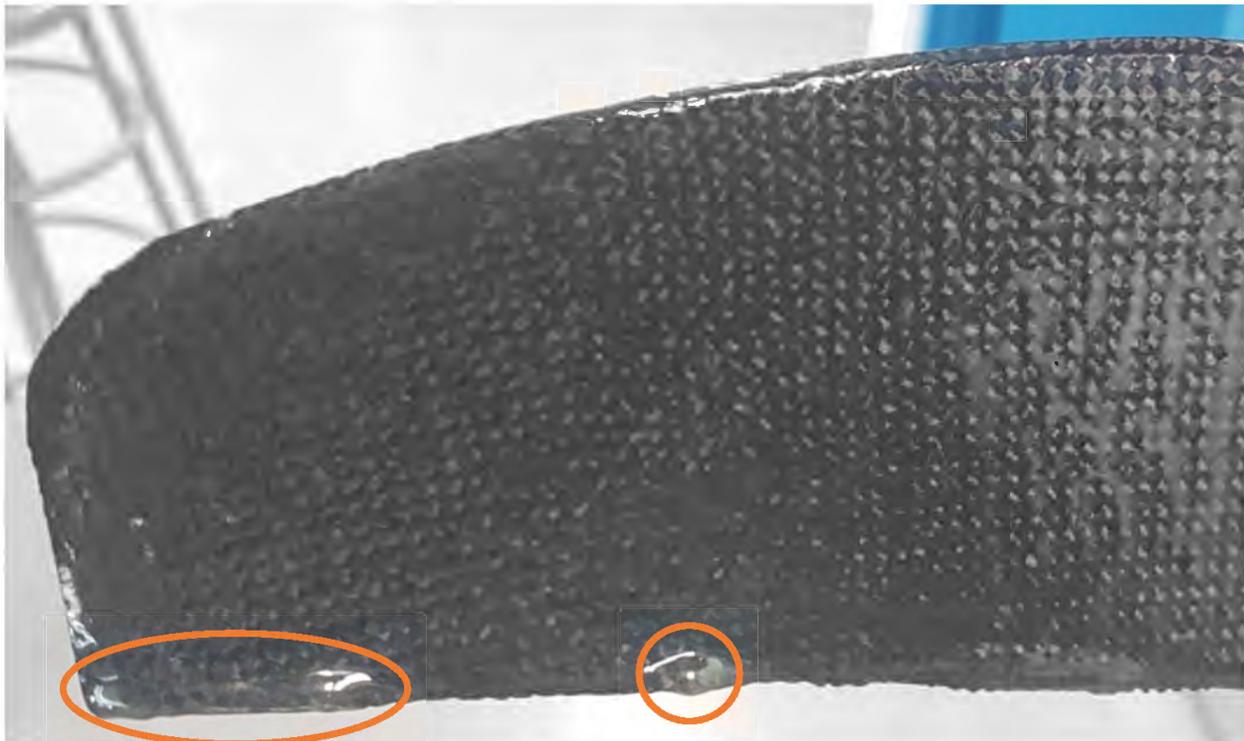


Figure 45: Epoxy Bubbles & Build-up

To let the epoxy dry, the wing was hung in the orientation shown above; the leading edge at the top and the trailing edge at the bottom. This eliminated the chance of the epoxy pooling up on the top or

bottom side. However, this caused all the excess epoxy to drip off the trailing edge of the wing as it dried. This resulted in a thicker layer of epoxy to form on the trailing edge of the wing and caused some epoxy bubbles to form. This produced a smooth, consistent finish on the top and bottom side of the wing but, due to the thick layer of epoxy and epoxy bubbles on the trailing edge, the trailing edge required a significant amount of sanding to remove the excess epoxy.

5.2 Final Result

Below is the completed prototype, fully assembled and attached to the provided mast.



Figure 46: Assembled Prototype

All the fasteners and connections surfaces fit and are properly aligned.

5.2.1 Fuselage



Figure 47: Fuselage Prototype

The fuselage is 1" wide, 0.5" thick and 27.5" long. It is made from 6061-T6 Aluminum and has been powder coated black to match the wings/mast and to add a protective and corrosion resistant finish. Through holes have been drilled to allow for the mast and wings to be secured with M8 fasteners. The holes have been countersunk so that the M8 fasteners are flush with the fuselage once installed.

5.2.2 Fasteners



Figure 48: Powder Coated Fasteners

The top of the M8 fasteners were powder coated black to match the fuselage; the threads were covered with heat resistant tape so that the threads were not powder coated.

5.2.3 Front Wing



Figure 49: Front Wing Prototype

The front wing has a wingspan of approximately 1 m and, including the height due to the dihedral angle, the overall height of the wing is 38 cm. The final finish consisted of very small pitting in the epoxy layer but not enough to affect the performance of the wing. Additionally, the folds in the carbon-fiber that occurred during the vacuum bagging process can be seen at certain angles, but the structural integrity of the carbon-fiber was not compromised.

5.2.4 Back Wing

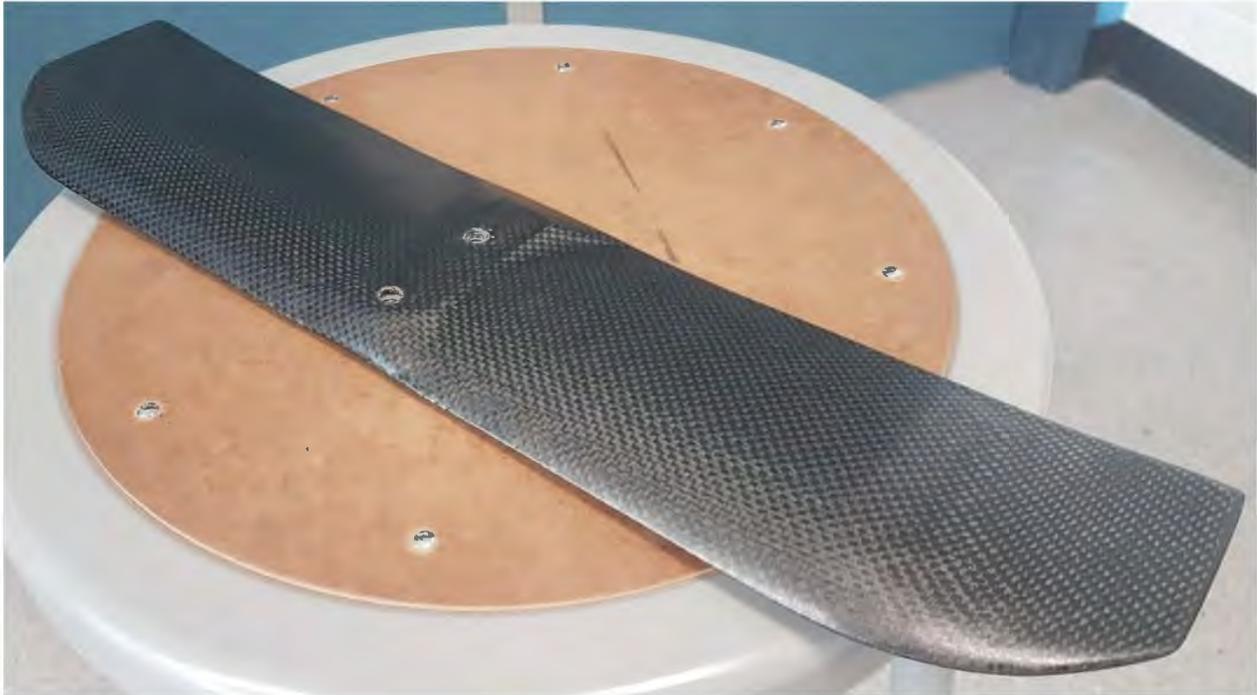


Figure 50: Back Wing Prototype

The back wing was a wingspan of 45 cm but has no dihedral or anhedral angle incorporated. The final finish is smooth and uniform with very little signs of pitting or inconsistencies in the surface finish. There were no folds in the carbon-fiber layer during the vacuum bagging, so the carbon-fiber pattern is consistent throughout the wing.

6 Conclusion

The objective of this project was to design and manufacture a hydrofoil. The hydrofoil is intended to be used for stand-up paddleboards and has been theoretically optimized for foil pumping. One concept was selected and further improved upon to what the final design of the hydrofoil is currently. Through unforeseen problems the team was able to successfully manufacture a prototype of the hydrofoil design.

The final prototype produced contains a few defects and the slight flaws that are present are purely aesthetic and will not affect the performance of the hydrofoil. The main flaws present in the manufactured prototype are on the wing in the form of minor pitting. This could be fixed by applying another layer of epoxy, but the tight time constraints prevented the additional epoxy layer from being applied. Additionally, the areas in which the carbon-fiber layers folded during vacuum bagging are visible through the epoxy layer, but it does not affect the structural integrity of the wing or its performance.

6.1 Future Work

Although the manufactured prototype was a success, there were a few modifications to the final prototype to consider in the future that could greatly ease the manufacturability and performance of each component of this hydrofoil.

6.1.1 Foam Core

Instead of cutting the wing core from MDF, the core could be made from foam. The CNC process would be very similar except that it would be much quicker to cut. Additionally, foam would be easier to produce a stock piece and would be much cheaper than MDF. Also, the foam core would be much lighter than MDF, decreasing the major source of weight in the wings.

6.1.2 Threaded Fuselage

However, due to the inability of threading the foam or adding threaded inserts to accommodate the M8 fasteners, the fuselage would then have to be threaded for the M8 Fasteners. Through holes would be drilled into the wing to accommodate the M8 fasteners.

6.1.3 Anodization to Replace Powder Coating

Powder coating is susceptible to damage and will show signs of wear/use over time. Anodization is much more visually appealing and will last longer than the powder coating, showing less signs of wear and damage. Additionally, the anodization process will not significantly affect the tolerances on the fuselage.

Bibliography

- [1] King of Water Sports, "Nobile Zen Hydrofoil," Kingofwatersports, [Online]. Available: <https://www.kingofwatersports.com/product?productid=nobile-zen-2017-hydrofoil&group=US>. [Accessed 20 October 2018].
- [2] C. Muller, "Design," SABDA Studios, [Online]. Available: <http://kitehydrofoil.com/design.html>. [Accessed 4 January 2019].
- [3] M. Sadraey, Aircraft Design: A Systems Engineering Approach, New Hampshire: A John Wiley & Sons, Ltd, 2013.
- [4] T. Vantol, "LET'S CHAT: CHOOSING A SURF HYDROFOIL," MACKite Boarding, March 5 2018. [Online]. Available: <http://www.mackiteboarding.com/news/lets-chat-choosing-a-surf-hydrofoil/>. [Accessed 15 January 2019].
- [5] Airfoil Tools, "NACA6409 9% (n6409-il)," [Online]. Available: <http://airfoiltools.com/airfoil/details?airfoil=n6409-il>. [Accessed 16 January 2019].
- [6] Airfoil Tools, "NACA 6412 (naca6412-il)," [Online]. Available: <http://airfoiltools.com/airfoil/details?airfoil=naca6412-il>. [Accessed 16 January 2019].

Request for Proposal

Development of a Recreational Hydrofoil

Project Overview

We at, Hydro Boarding Bros (HBB), are planning to sell a hydrofoil for a surf/paddle board.

Current designs for hydrofoils have been proven to work, but none have been scientifically optimized for performance. We are looking for a company that can design a hydrofoil, made with carbon fiber, and optimize the shape to create maximum lift for this application.

Recently, many hydrofoil surfers have taken to “foil pumping” to propel themselves forward without using the speed of a wave. This allows hydrofoil users to maintain speed while in flat, wave-less water. The design of the hydrofoil should incorporate optimization for “foil pumping” in order to gain and maintain speed as efficiently/effectively as possible.

Project Objective/Goals

The goal is to produce a hydrofoil design that outperforms the currently available hydrofoils at a competitive price. The product should be designed and marketable for the average water sports enthusiast.

The CONTRACTOR will analyze the desired performance parameters and their relationship to the design of the hydrofoil; The CONTRACTOR will then develop a design and select a wing profile most suitable for the desired performance goals. Additionally, the “foil pumping” method of propulsion will be analyzed to determine if this method can be optimized too.

Scope

The focus of this project is on the hydrofoil design; Mainly to determine the desired performance parameters, and how different design parameters can affect performance.

Existing boards and attachment systems work sufficiently; therefore, they are not within the scope of this project. However, the design of the mast is included in the scope of this project.

Project Timeline

This project is required to be completed by the **end of May 2019**; All the project deliverables must be completed and submitted by this date.

Mid-project reviews and milestones will be outlined in the project proposal by the CONTRACTOR

Technical Requirements

The final design of the hydrofoil must be competitive in performance and functionality to current hydrofoils available. Lightweight is a key requirement, so the hydrofoil must be made of carbon-fiber or another lightweight and high-performance material. The hydrofoil must also produce sufficient lift force at speeds commonly reached when surfing or paddle boarding. Additionally, the hydrofoil design must be compatible with most surf/paddle boards.

Budget

Currently, there is no definite budget set for the research, development and production of the hydrofoil prototype. However, the final product must be marketable for around \$1500-3000 MSRP to be competitive with current products available.

Project Deliverables

The CONTRACTOR will be responsible to produce the following by the end of the agreed upon deadline:

- Technical Analysis of effects of hydrofoil shape
- Conceptual & detailed design
- Manufacturing drawings
- Working prototype
- Final design presentation

Evaluation

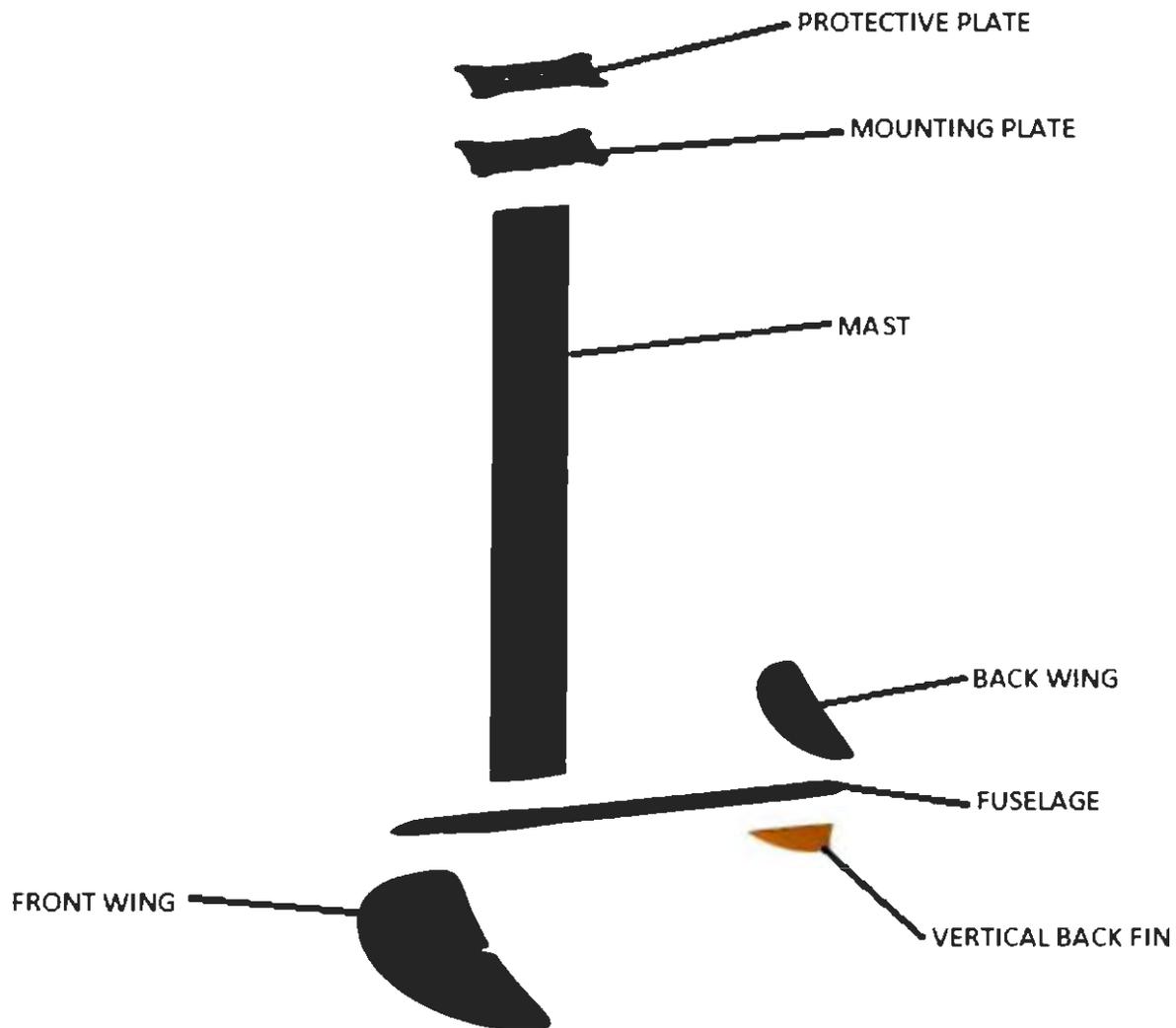
The company most qualified and capable of producing a quality product with the lowest cost will be chosen. We will be looking at proposal with a clear timeline and budget, and a company capable of producing a prototype by the deadline.

Personnel with technical knowledge and experience in the fields of Fluid Mechanics, aerodynamics/wing theory and manufacturing processes involving carbon fiber are strongly preferred.

Standard Info & Nomenclature

Surf Foil Design & Manufacture

Component Naming Convention



<https://www.kingofwatersports.com/product/nobile-zen-hydrofoil/nobile-zen-2017-hydrofoil>

Common Terminology

Foil Pumping – The act of forcing down the board with the front foot in order to propel the board forward.

Fuselage - is the part that holds everything together at the bottom. It allows for attaching a front wing, a rear wing and connects onto the mast

Wake – the waves created by a passing vessel

SUP – Stand Up Paddleboard

Pitch Stability - A pitch stable board will resist pitch movement

Aspect Ratio - Aspect ratio is the ratio of the wingspan to the area of a wing. A wing with a short chord and long wingspan has a very high aspect ratio and vice versa.

Tuttle Box - An alternative mounting method to attach the mast to the board, where the attachment is located inside the board.

Plate Mount - A type of mounting system for attaching mast to board

Chord Length - The length of the component as measured parallel to the board.

Span - Measurement tip to tip of the wing

Lift - The upwards force generated by moving fluid over the wing profile

Drag - The frictional resistance force generated in opposition to the direction of movement by the fluid

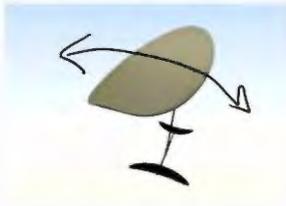
Anhedral - the curve of the wing downwards

Dihedral - is a curve in the opposite direction (upwards) and is normally found on aircraft such as gliders to give them roll stability

<http://kitehydrofoil.com/design.html>

ROLL

Roll is best explained by a picture



PITCH

Pitch is the up or down wards pointing angle of the board:



YAW

Yaw is a motion where you steer the board left or right like in this picture:

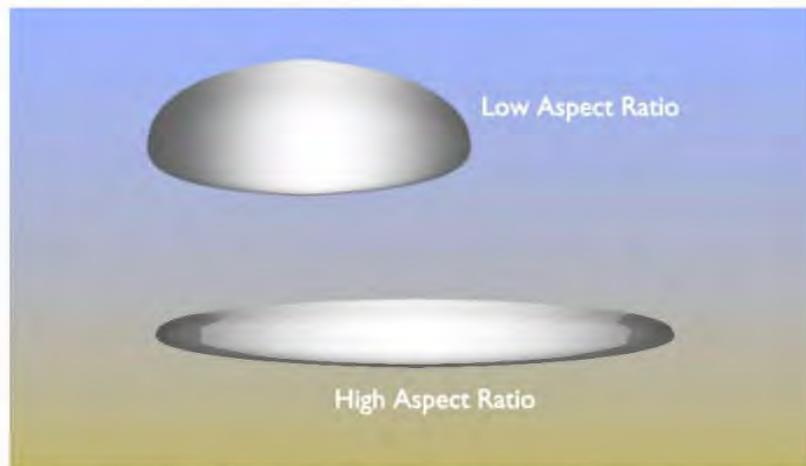


CHORD

Chord is the length (not wingspan) of a wing. It is the distance from the front to the back of a wing.

ASPECT RATIO

Aspect ratio is the ratio of the wingspan to the area of a wing. A wing with a short chord and long wingspan has a very high aspect ratio and vice versa.



Lets tackle the keel first, as it is probably the easiest one to design, but definitely not the easiest one to build. [THE KEEL..](#)

mast: is the part between the board and the fuselage of the hydrofoil. It needs to be very low drag since it is not used for lift, but it needs to be as stiff as possible.

Most hydrofoils have the mast and fuselage as one piece, which allows a lighter or stronger hydrofoil than making it removable

Design Parameters:

Wing Aspect ratio - The ratio of wing surface area to wingspan (applicable to both front and back wings)

Wing profile Aspect ratio - The ratio of wing chord length profile height (applicable to both front and back wings)

Wing sweep angle - The angle formed between the direction of travel and the lofted path of the wing profile.

Forward swept wing - A wing that when viewed from above sweeps forward from the symmetry line at the mast

Wing profile - The cross-sectional profile of the wing created by slicing the wing with an imaginary plane that is parallel to the mast (applicable to both front and back wings)

Wing surface area - The surface area of the wing (applicable to both front and back wings)

Span - The distance from wingtip to wingtip (applicable to both front and back wings)

Cord length - The length of any component that is measured parallel to the intended direction of travel (applicable for board, mast, front wing, back wing, fuselage)

Anhedral - Downwards sweeping wing profile when viewed from the front. For anhedral wings, when measured between each wing from top surface to top surface the angle will be >180 degrees (applicable to both front and back wings)

Dihedral - Upwards sweeping wing profile. For dihedral wings, when measuring the angle between each wing from top surface to top surface will be <180 degrees (applicable to both front and back wings)

Fuselage length - The length of the fuselage, measured from end to end

Mast Length - The length of the mast, measured between the board and fuselage attachment points

Performance Parameters:

Drag - The resistance force created by the water traveling over the foil

Lift - The amount of force generated by the foil as it travels through the water

Pitch stability - Resistance to the board lifting front to back

Roll stability - Resistance to the board rotating side to side

Yaw stability - Resistance to changes in yaw

Lift velocity - The velocity required to achieve lift (min velocity)

Maneuverability - The ability of the board to maneuver through turns

Buoyancy - Lifting force due to displaced water

Max weight - Maximum weight in which the board remains operational

Operational Velocity Range - the velocity range in which the hydrofoil is providing useful lift

Lift to Speed Ratio - the amount of lift generated per unit of speed. A curve defined by the lift coefficient and Reynolds number, from which the lift at a given velocity can be determined

Lift to Drag Ratio - the amount of lift generated per unit of drag force



Appendix C Design and Performance Parameters

Surf Foil Design & Manufacture

Design & Performance Parameters Report

MECH 8190 - Capstone Project

Submission Date: Nov 22nd, 2018

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Brandon Wu

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Abstract

The following report links the performance parameters to the design parameters of a recreational surf foil. Linking the design to performance is critical in order to successfully create a stable and responsive hydrofoil that addresses the requirements of the consumer. Although the list of design and performance parameters is not exhaustive, the dominant parameters have been identified.

Design Parameters	Performance Parameters	Correlation
Fuselage Length	Pitch Stability	+
	Yaw Stability	+
Mast Length	Yaw Stability	-
	Roll Stability	-
	Max Operational Velocity	+
Front Wing Aspect Ratio: Top	Max Operational Velocity	+
	Lift / Speed	-
	Lift: Drag Ratio	-
	Max Weight of User	-
Front Wing Aspect Ratio: Side	Lift: Drag Ratio	+
	Max Weight of User	+
Rear Wing Aspect Ratio: Top	Pitch Stability	-
	Roll Stability	+
Rear Wing Aspect Ratio: Side	Pitch Stability	+
Vertical Fins	Yaw Stability	+
	Roll Stability	+
Anhedral Wing	Roll Stability	-
Dihedral Wing	Roll Stability	-
Total Wing Surface Area	Max Operational Velocity	+
	Max Operational Velocity	-
	Lift / Speed	+
	Lift: Drag Ratio	+
	Roll Stability	+
Angle of Attack	Lift: Drag Ratio	+
	Max Weight of User	+

Positive Correlation (+): An increase in Design Parameter results in an increase in the performance parameter

Negative Correlation (-): An increase in Design Parameter results in a decrease in the performance parameter

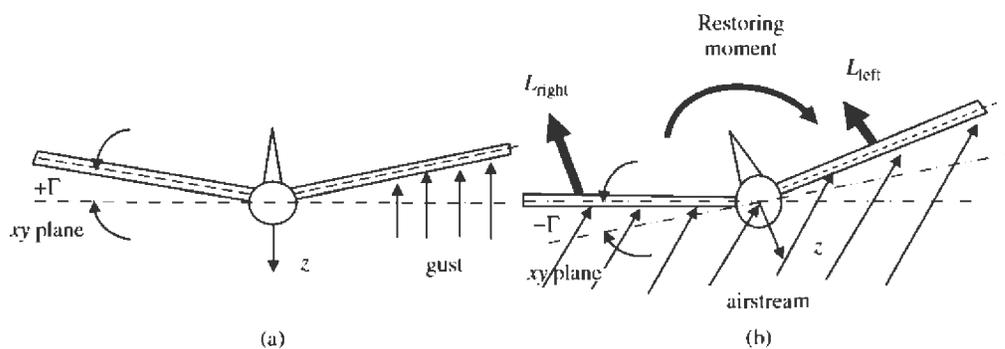
Design Parameters vs Performance Parameters

Anhedral Front Wing

The hydrofoil acts similarly to a pendulum due to the length of the mast and the position of the surfer's mass. When the surfer rolls the board away from a level position, the lift generated by the front wing causes a sideslip. If the wings are angled downwards, then a banking motion in cause a greater angle of attack on the high portion of the wing than on the lower side, this assist generating lift and prevents a wing's tendency to self level. [1]

An anhedral front can be desirable due to the resulting increase in maneuverability by allowing a banking turn to be performed more easily. The drawback is the reduction of roll stability. An anhedral front wing allows for a more forgiving ride when riding upwind as the wingtips are less prone to push out of the water when banking the board. The additional vertical wing area add yaw stability. [2]

Anhedral wing shape allows for foiling to be achieved at lower speeds but tends to reduce to the max operating speed. [3]



In some references, it is called *dihedral stability*, since a wing dihedral angle provides

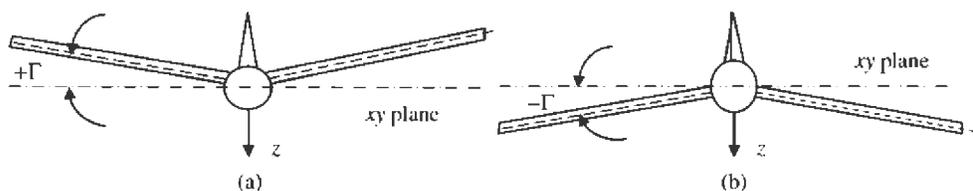


Figure 5.49 (a) Dihedral and (b) anhedral (aircraft front view)

Fig 1: Effect of Dihedral and Anhedral Angles [4]

Anhedral Rear Wing

An anhedral rear wing increases the maneuverability of the surf foil but decreases the pitch stability. The effect is not as dramatic as increasing the anhedral angle of the front wing. This is due to the significantly smaller surface area of the rear wing when compared to the front wing. [3]

Dihedral Front Wing

Dihedral front wings are uncommon in surf foil design as the resulting increase in stability comes at a significant decrease in maneuverability [2]. This is due to the dihedral angle introducing a restoring moment which will oppose a rolling motion introduced by the rider which is required to turn the board. Dihedral wings will not be considered further as the reduction in maneuverability is too significant to justify further investigation.

Dihedral Rear Wing

Dihedral rear wings can be found on some hydrofoil designs, such as on the Spotz brand. [4] As the rear wing is generally used to provide stability, the decrease in maneuverability may be warranted in some designs.

Mean Chord Length: Wings

The mean chord length is the centerline length. For symmetrical profiles such as the one shown below the chord length is the length of the horizontal line drawn from front to back on the wing.

Note: For wings that have camber (asymmetrical profile) the camber line is a curve.

Aspect Ratio: Front Wing - Side View

The aspect ratio is the ratio of cross-sectional area to mean chord length. The lift force is affected by changes to this parameter by the equation:

$$F_L = \int_0^c \Delta P_l \cos \beta_l - \Delta P_u \cos \beta_u \quad [5]$$

where β represents the angle of the slope of the wing surface at some position along the chord for the upper and lower surface.

Thus, if area is fixed and length is changed the slopes, β , change and effect the lift force.

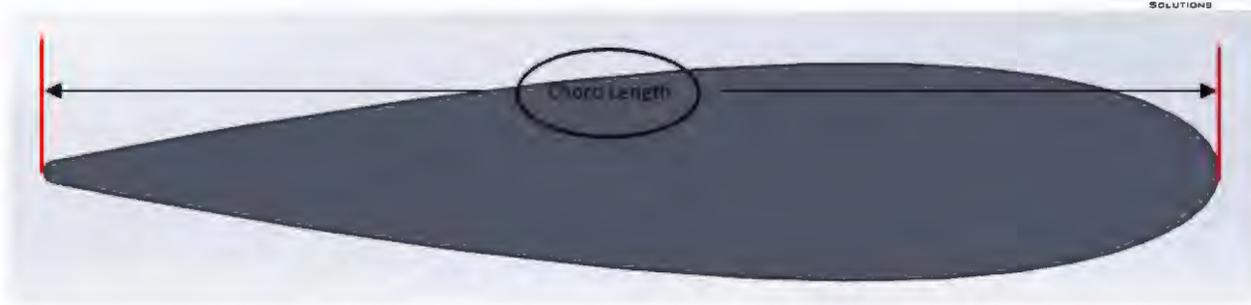


Fig 2: Cross section of a NACA 0018 wing profile, viewed from the side.

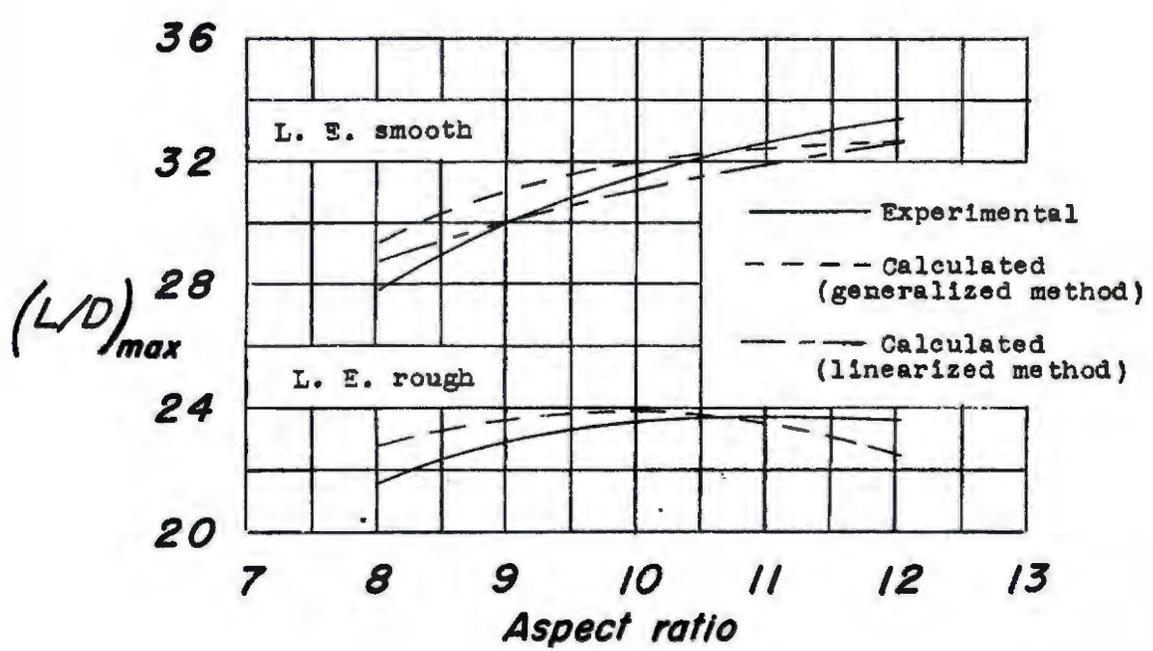


Fig 3: Chart of the effect of increasing the aspect ratio with respect to the lift to drag ratio [7]

Increasing the Aspect Ratio of the front wing viewed from the side will result in a increase of the Maximum Operational weight because it produces more lift and allows for more weight.

Aspect Ratio: Front Wing - Plan View

The aspect ratio is the ratio of wingspan to mean chord length.

In addition to the formula shown above, the lift force can be calculated by:

$$F_L = C_L \frac{\rho}{2} V^2 SA$$

[5]

Thus, as the surface area of the wing (shown in Fig 2) increases the lift force increases.

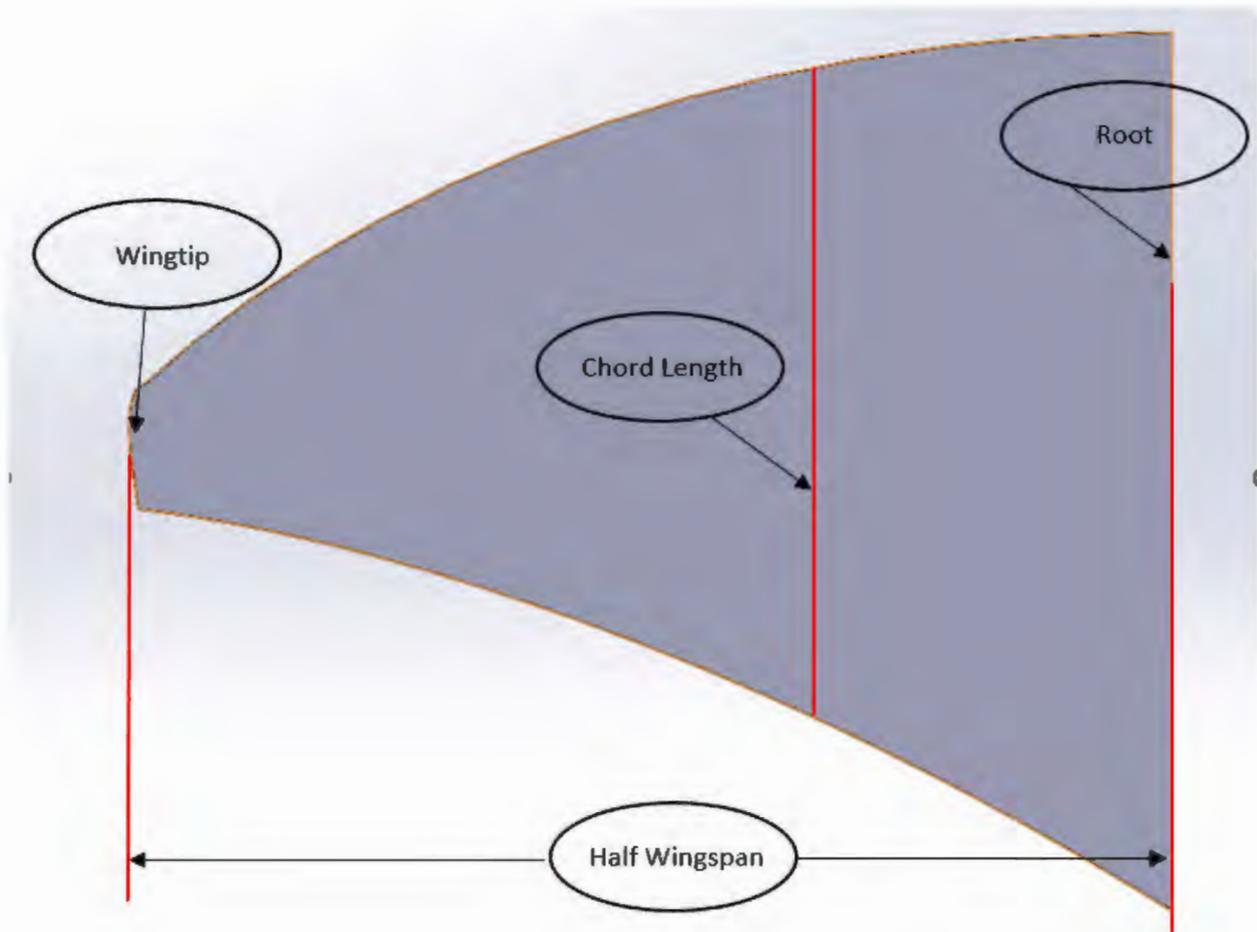


Fig 4: Cross section of a NACA 0018 wing profile, viewed from the top.

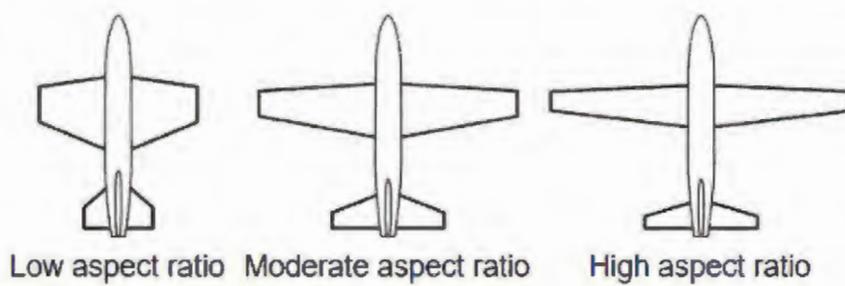


Fig 5: Wing aspect ratios [6]

Low aspect ratio wings are more structurally efficient whereas, high aspect ratio wings are more aerodynamically efficient. [6]

Aspect Ratio: Rear Wing - Side Profile & Top Profile

The definition of aspect ratio for the rear wing is the same as the front wing. However, typically the rear wing generates lift in the opposite direction to the front wing. This downward lift provides pitch stability when balanced by the rider shifting their weight forward.

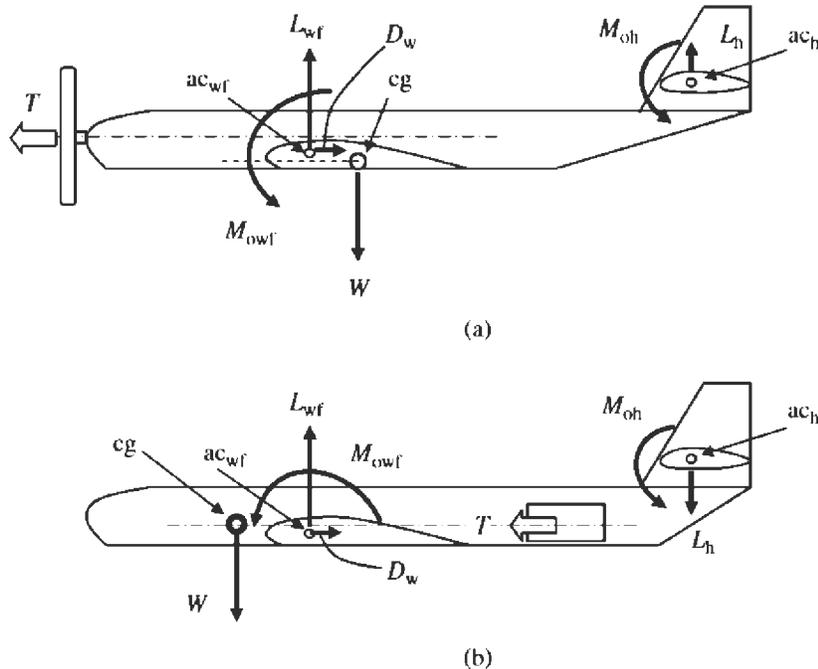


Figure 6.2 A conventional aircraft in longitudinal trim. (a) cg aft of ac_{wf} ; (b) cg forward of ac_{wf}

Fig 6: Design of lift forces for different centres of gravity [4]

Wing Sweep: Front Wing & Rear Wing

The wing profile refers to the lofted path that the wing cross section is projected along to create a solid shape. It can be seen in Fig. 2 at the top of the image (the elliptical path). It is the leading edge of the wing.

The wing profile can be backswept, delta, forward swept, or straight each with their own advantages and drawbacks.

Forward swept wings are known to have higher maneuverability. They also create more lift than comparable sized backswept wings by directing wingtip vortices from the wingtips to the fuselage [7] One problem is that forward swept wings is that they create drag when experiencing yaw (one wingtip is farther forward than the other) and this drag causes more yaw [7].

Delta wings can be made stiffer than swept wings as their root (inboard) chord length is typically longer. A common problem with delta wing aircraft is that they are prone to stalling at steep attack angles. [8]

Backwards swept wings are easier to recover from a stall than forward swept wings [7] but are more prone to stalls than forward swept wings [d].

Straight wings are more structurally efficient than the others. [6]

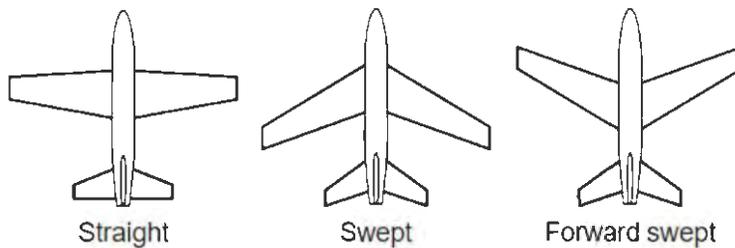


Fig 7: Wing sweep configuration examples [6]

Chord Variation Along Wingspan

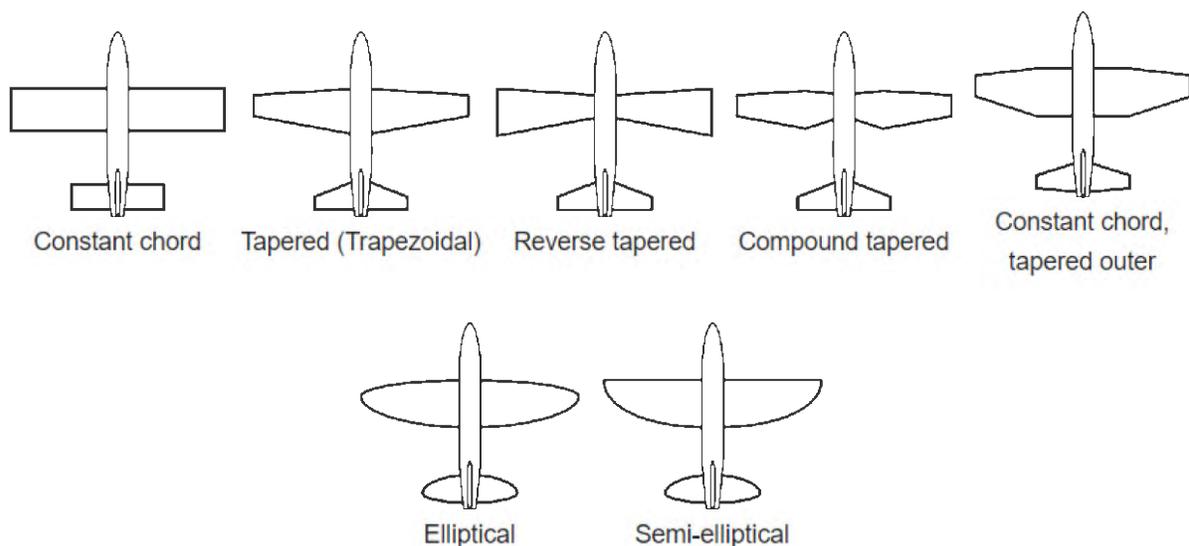


Fig 8: Picture showing the chord variation along wingspan [6]

Chord variation along the wingspan directly relates to the wing surface area and thus to lift. For example, an elliptical wing is able to generate more lift than a constant chord wing and it saves weight at the wing tip.

Total Surface Area and its relationship with Drag and Lift

Drag between a body in a moving fluid is defined by the following equation:

$$D = \frac{1}{2} C_d \rho v^2 A_{ref}$$

Where C_d is the drag coefficient, ρ is the fluid density, v is the fluid velocity, and A_{ref} is the reference area? [9] The reference area changes depending on whether drag caused by resistance to flow (i.e. form

drag) or friction between the fluid and wing surface (i.e. skin friction). Drag due to skin friction depends on the total surface area, where form drag depends on the projected area perpendicular to the direction of flow. [1] This section pertains to skin friction; for more information on form drag see Angle of Attack below.

As seen in the above equation, the drag force generated is directly proportional to the area of the body for a given set of fluid properties and conditions. If the surface area is doubled, so is the drag due to skin friction.

Total Surface Area: Front and Rear Wings

In traditional aircraft design, the main function of the front wing is to provide lift for flight, while the main function of the rear wings, is to provide flight stability, namely pitch stability. [10] For this reason, their size, and therefore surface areas differ significantly.

As with drag, lift also depends on surface area. Lift is defined by the following equation:

$$L = \frac{1}{2} C_l \rho v^2 A_s$$

Where C_l is the lift coefficient, ρ is the fluid density, v is the fluid velocity, and A_s is the surface area over which the fluid flows. [11] Similar to drag, lift is directly proportional to wing surface area and so it follows that the front wings should have a large surface area if its main function is to produce lift.

The rear wings also produce lift, but this traditionally is downwards (i.e. a tail down force) to balance the moment about the centre of gravity produced by the lift of the front wings, as depicted in the figure [FIGURE#] below.

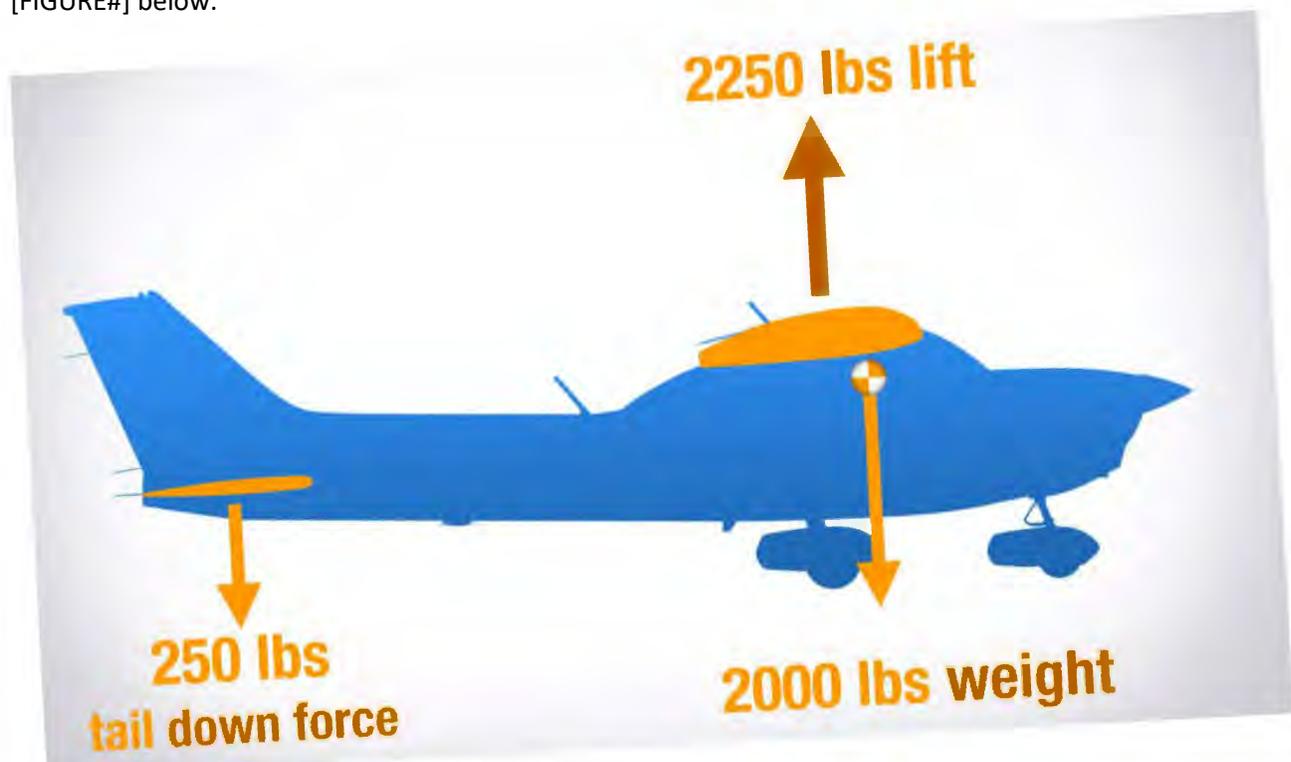


Fig 9: [12]

Because both the drag and lift forces are proportional to surface area, it follows that there is an optimal rear wing surface area for a given fuselage length. Explicitly, that is a surface area that minimizes the drag, while producing enough lift to balance the moment generated by the front wing to achieve pitch stability.

Vertical Fins

Vertical fins are typically mounted on the rear wing or the rear portion of the fuselage in order to provide yaw and roll stability at higher speeds. Vertical wings towards the front are less common because the mast essentially acts as a vertical fin. If the vertical fin is incorporated in the fuselage, it can help provide structural strength and stiffness to the member.

Fuselage Length & Size

The length of the fuselage determines the location of the front and rear wing with respect to each other and where the wings rest under the board. A long fuselage increases the pitch and yaw stability but decreases the maneuverability in the vertical direction for a given set of front and rear wing surface areas. This is due to the increased maximum reaction moment that is created. Increased pitch stability is not always an improvement to the design as pitch stability tends to increase naturally when higher velocities are achieved. Too much pitch stability will slow the rider's response time, which is undesirable when surfing in choppy conditions with large waves, where the length of the mast is not large enough to cruise through the chop. [2]

A thick fuselage will introduce more drag to the hydrofoil, decreasing the maximum operation velocity and increasing the amount of applied force required for motion. The thickness is determined by the strength required to prevent critical failure.

Mast Chord Length

Typically the chord length of the mast is around 100 mm. In order to provide sufficient strength and stiffness, a sufficient thickness must be selected. A lack of stiffness in this member will significantly decrease the yaw, pitch and roll stability, as well as the maneuverability. Decreasingly the chord length requires an increase in mast thickness, which will generate more drag and decrease maneuverability. [3]

Mast Length

Long masts can raise the surfer higher out of the water but can be difficult to control as the greater the length of the mast, the greater the moment acting on the foil. The mast creates a pendulum action as the center of mass of the rider sits much higher than the foil underneath them, which decreases the pitch and roll stability. Short masts are recommended for novice riders as short masts feel more responsive. Long masts are used in racing as they provide a smoother ride across large waves, cruising above the chop and in the case of a kiteboard, a better upwind angle can be used. [13]

Angle of Attack

As the foil moves through water, the wings centerline of the wings is often not perpendicular to the velocity, but rather at some inclined angle. This angle is referred to as the angle of attack. Depending on the projected area of the wing, a considerable amount of lift is generated as the angle of attack is increased. As a result of the increased lift, the effects of drag resistance to fluid motion (not frictional drag) is generated. At too great an angle, the flow becomes separated and stalls, which would almost certainly cause the rider to crash. Predicting the stall point is difficult to determine by calculation and is therefore typically determined through experimentation. [14] Although the increase in the angle of attack will create more lift, increasing the angle beyond 15° typically leads to diminishing returns.

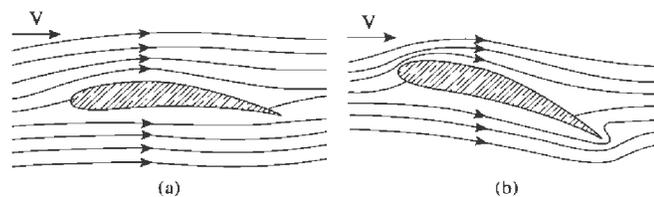


Figure 5.6 Flow around an airfoil: (a) Small angle of attack; (b) Large angle of attack

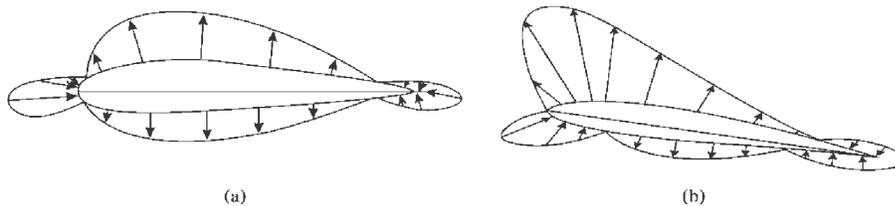


Figure 5.7 Pressure distribution around an airfoil: (a) Small angle of attack; (b) Large angle of attack

Fig 10: Pressure distribution of an inclined and not inclined airfoil [4]

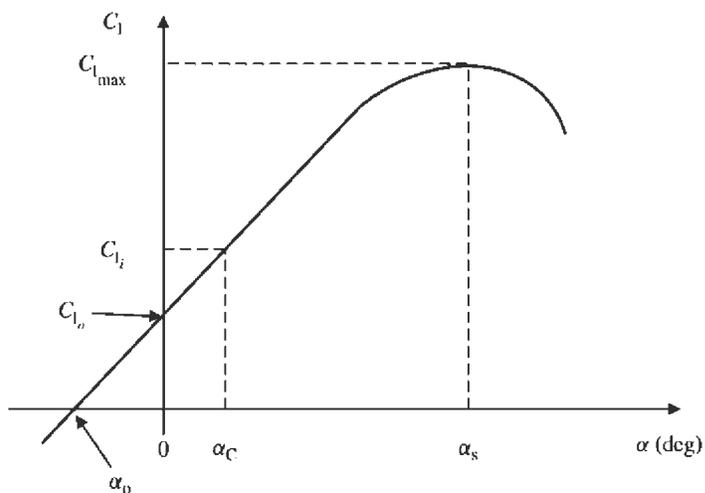


Figure 5.11 The variations of lift coefficient versus angle of attack

Fig 11: Increasing lift coefficient with an increasing angle of attack [4]

Common Dimensions

Mast Length: 60-85cm

Mast Chord Length: 120-137mm

Mast Thickness: 12-14mm

Fuselage Length: 60-90cm

Front Wingspan: 50-100cm

Front Wing Aspect Ratio (Top): 2.5- 6.5 [L/Chord Length]

Front Wing Thickness: 3/16" -1/2" at thickest point (0.5-1.3cm)

Rear Wingspan: 30-70cm

Rear Wing Aspect Ratio (Top): 3-6 [L/Chord Length]

References

- [1] RC Powers, "Anhedral Wings :: Detailed explanations of anhedral plane designs," RC Powers, 16 Feb 2009. [Online]. Available: <https://www.rcpowers.com/community/threads/anhedral-wings-detailed-explanations-of-anhedral-plane-designs.234/>. [Accessed 4 Jan 2019].
- [2] C. Muller, "Design," SABDA Studios, [Online]. Available: <http://kitehydrofoil.com/design.html> . [Accessed 4 Jan 2019].
- [3] Warwickl, "Stabaliser Wing," Seabreeze, 3 Jun 2018. [Online]. Available: <https://www.seabreeze.com.au/forums/Stand-Up-Paddle/Foiling/Stabaliser-wing-which-way-up?page=1> . [Accessed 4 Jan 2019].
- [4] PB Kiteboarding, "Spotz Tuna 58cm 61cm Lightwind," PBK, 2018. [Online]. Available: https://www.pbkiteboarding.com/Kiteboarding-Snowkiting-Equipment/Spotz_Tuna_Hydrofoils_Kitefoils_Kiteboarding_Kitesurfing_Foils/Spotz_Tuna_Hydrofoils_Kitefoils_Kiteboarding_Kitesurfing_Foils.html. [Accessed 4 Jan 2019].
- [5] D. F. W. Riefels, "Aerofoil Sections," Butterworths, London, 1961.
- [6] Wikipedia, "Wing Configuration," Wikipedia, 10 Dec 2018. [Online]. Available: https://en.wikipedia.org/wiki/Wing_configuration#Chord_variation_along_span. [Accessed 4 Jan 2019].
- [7] Wikipedia, "Forward-swept wing," Wikipedia, 2 Jan 2019. [Online]. Available: https://en.wikipedia.org/wiki/Forward-swept_wing. [Accessed 4 Jan 2019].
- [8] Wikipedia, "Delta wing," Wikipedia, 9 Dec 2018. [Online]. Available: https://en.wikipedia.org/wiki/Delta_wing. [Accessed 4 Jan 2019].
- [9] N. Hall, "The Drag Equation," NASA, 5 May 2015. [Online]. Available: <https://www.grc.nasa.gov/www/k-12/airplane/drageq.html> . [Accessed 4 Jan 2019].
- [10] Federal Aviation Administration, "Pilot's Handbook of Aeronautical Knowledge," U.S. Department of Transportation, Oklahoma City, 2016.
- [11] T. Benson, "Modern Lift Equation," NASA, 5 Apr 2018. [Online]. Available: <https://wright.nasa.gov/airplane/lifteq.html>. [Accessed 4 Jan 2019].
- [12] A. Udris, "What Are Canards, And Why Don't More Aircraft Have Them?," BoldMethod, 14 Aug 2014. [Online]. Available: <https://www.boldmethod.com/learn-to-fly/aircraft-systems/canards/>. [Accessed 4 Jan 2019].
- [13] Foilever, "Technical Terms Kitefoil and Windfoil," Foilever, 2017. [Online]. Available: <http://www.foilever.com/en/content/11-technical-terms-kitefoil-windfoil> . [Accessed 4 Jan 2019].
- [14] N. Hall, "Inclination Effects on Lift," National Aeronautics and Space Administration, 5 Apr 2018. [Online]. Available: <https://www.grc.nasa.gov/www/k-12/airplane/incline.html> . [Accessed 4 Jan 2019].
- [15] N. Hall, "Airplane Parts and Function," NASA, 5 May 2015. [Online]. Available: <https://www.grc.nasa.gov/www/k-12/airplane/airplane.html>. [Accessed 4 Jan 2019].

- [16] T. V. B. C. W. a. R. R. G. Robert H. Neely, "EXPERIMENTAL AND CALCULATED CHARACTERISTICS OF SEVERAL NACA 44-SERIES WINGS," Langley Memorial Aeronautical Laboratory, Washington, 1947.
- [17] M. H. Sadraey, AIRCRAFT DESIGN A Systems Engineering Approach, New Hampshire: A John Wiley & Sons, Ltd., Publication, 2013.



Appendix D Preliminary Design Review

Preliminary Design Review
for the Design and Manufacturing of a Surf Foil

Brian Leung

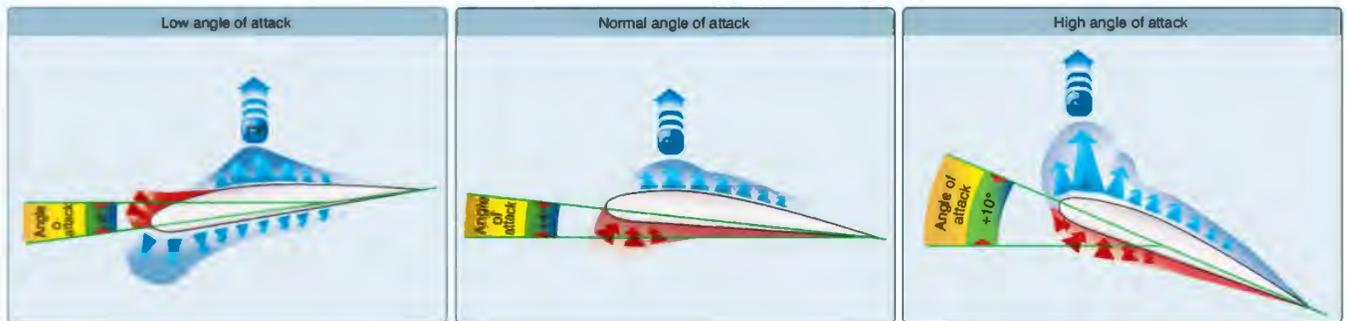
Robin Chahal

Brandon Wu

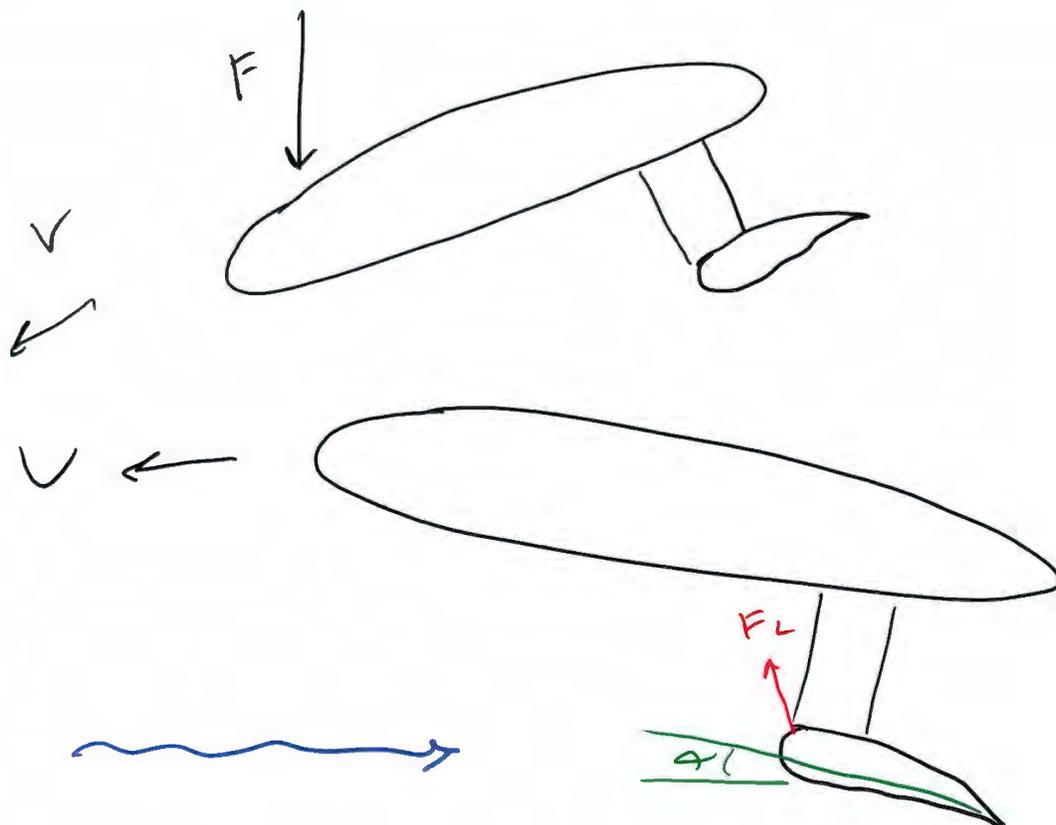
Design Requirements

We are designing the hydrofoil for stand-up paddle board and optimizing it for foil pumping. Typically, standup paddle boards are over 8 ft long to have enough volume to remain buoyant but we will be designing for a board that's between 5-6 ft. For this application we need enough lift for a relatively bigger board but also have the best lift to drag coefficient to effectively allow for foil pumping.

Foil Pumping Physics



<https://www.instagram.com/p/BlJg2fpD7m8/>



Calculations

NACA Profile

$$F_L = C_L \frac{\rho V^2}{2} A \Rightarrow C_L = \frac{2F_L}{\rho V^2 A}$$

assuming:

$m = 80 \text{ kg}$
 $\rho = 997 \frac{\text{kg}}{\text{m}^3}$ (water)
 $V \approx 3 \text{ m/s}$ ($\approx 11 \text{ km/h}$)
 $A \approx 0.15 \text{ m}^2$

$$Re = \frac{VL}{\nu} = \frac{3 \text{ m/s} (0.2 \text{ m})}{9.7937 \times 10^{-7} \text{ m}^2/\text{s}}$$

$$= \boxed{612 \times 10^3}$$

$$\therefore C_L = \frac{2(80 \text{ kg})(9.81)}{0.15 \text{ m}^2 \left(\frac{997 \text{ kg}}{\text{m}^3} \right) (3 \text{ m/s})^2} = \boxed{1.17}$$

with our assumptions, we want a lift coefficient of around 1.2

choose NACA 6409 9% or NACA 6412
at around $\alpha \approx 5^\circ$

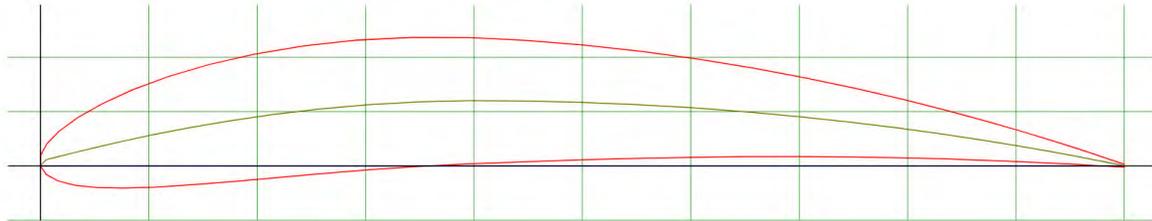
Determined the minimal lift coefficient required to start lifting is a $C_L=1.2$

NACA Profile

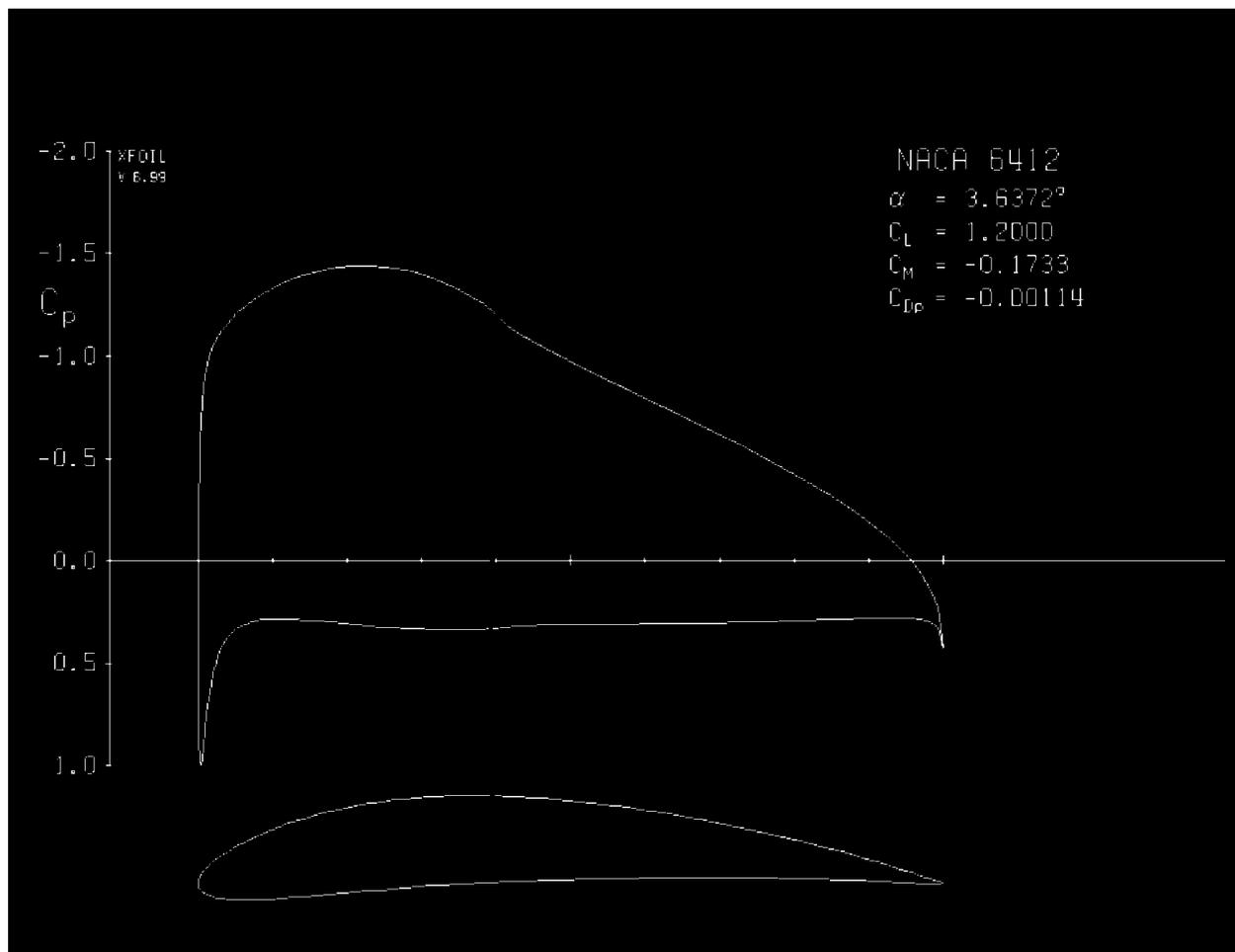
Chose a NACA profile that could achieve a $C_l=1.2$ at an $\alpha=3.6^\circ$

NACA 6412 (naca6412-il)

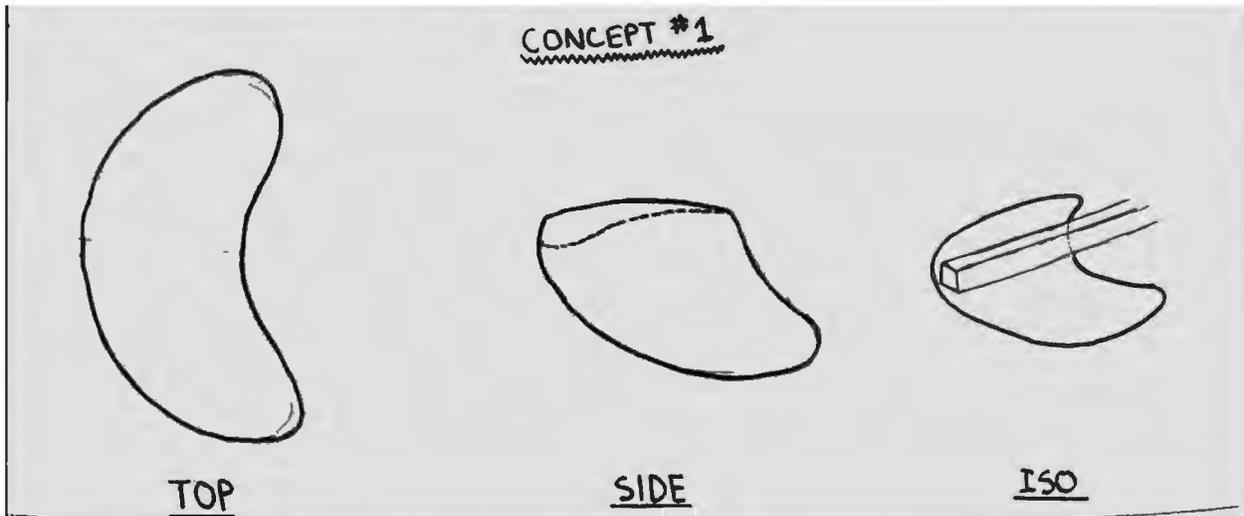
NACA 6412 - NACA 6412 airfoil



Pressure distribution of the NACA profile at $\alpha=3.6^\circ$



Concepts

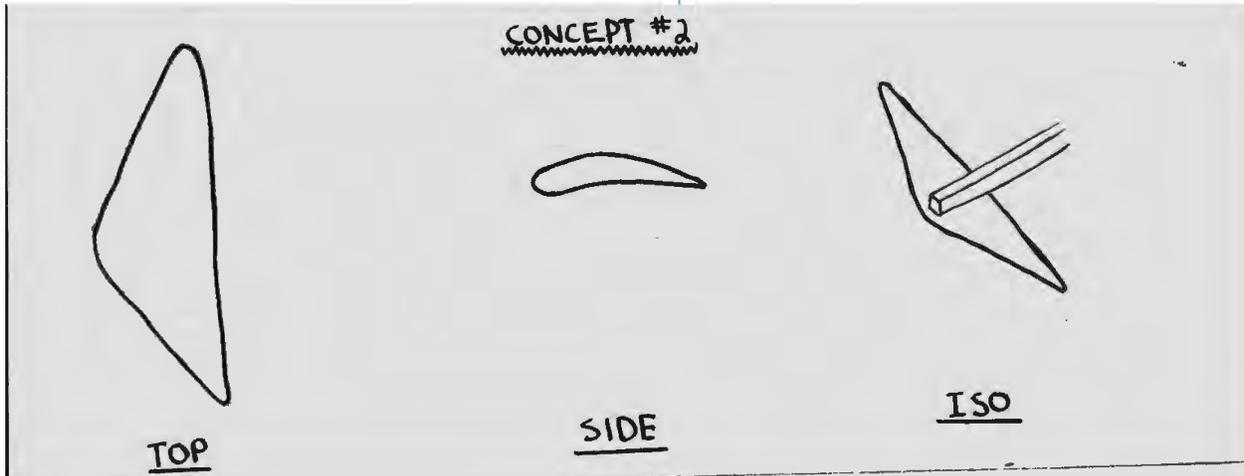


PROS

Highest Lift
Higher Operational Weight

CONS

High Drag
Lower Operational Velocity

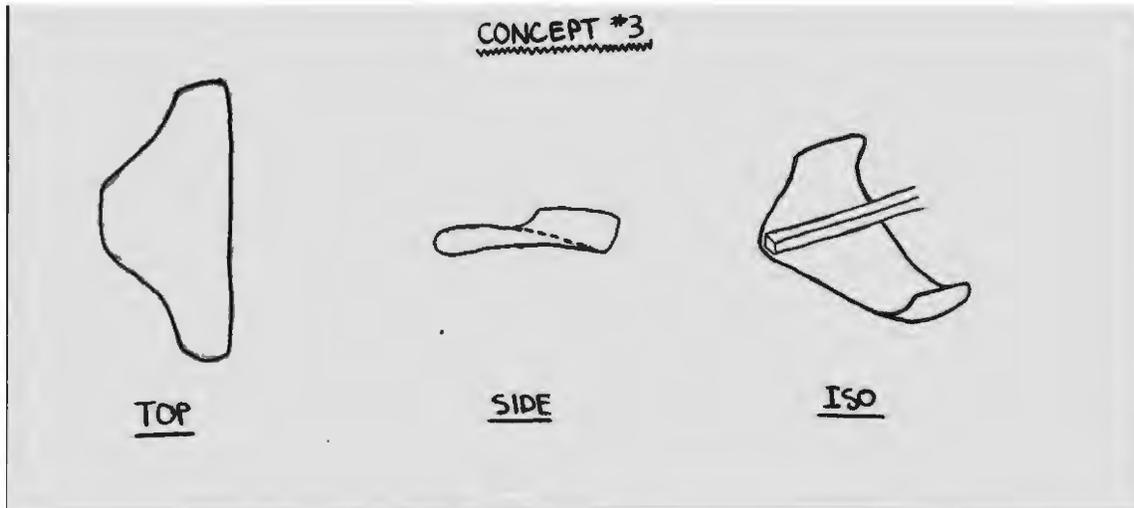


PROS

Minimal drag
High lift to drag coefficient
Simple
High operational velocity

CONS

Long wingspan
Neutral maneuverability and stability
Lower operational weight



PROS

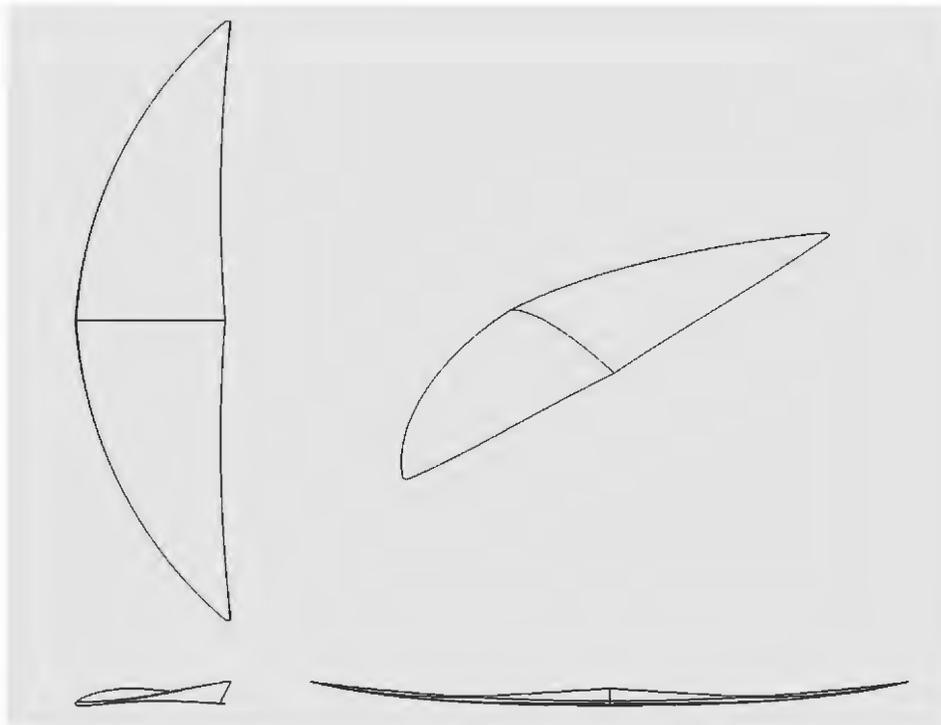
High Roll Stability
Shorter wing span
Innovative design

CONS

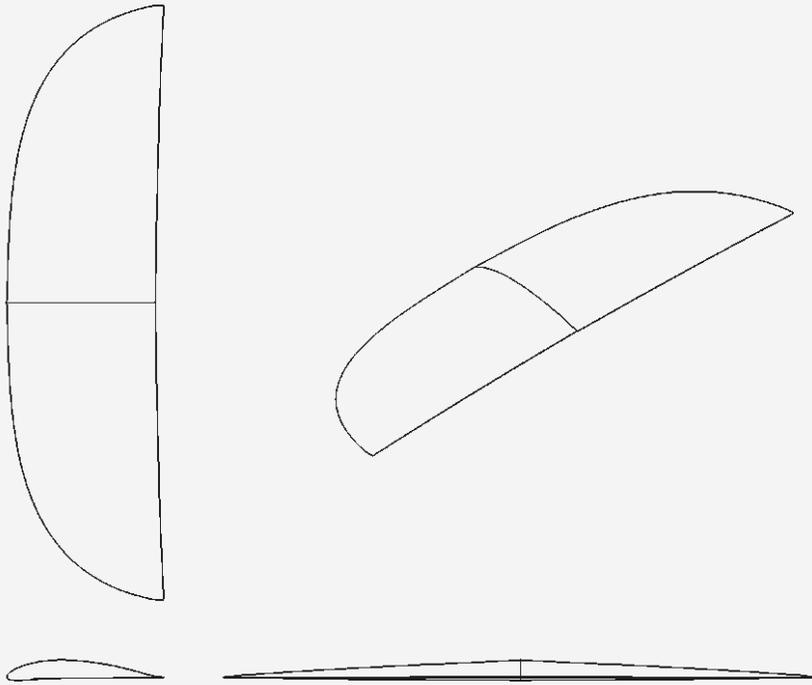
Less maneuverable
Lower operational weight
Lower operational velocity

Models

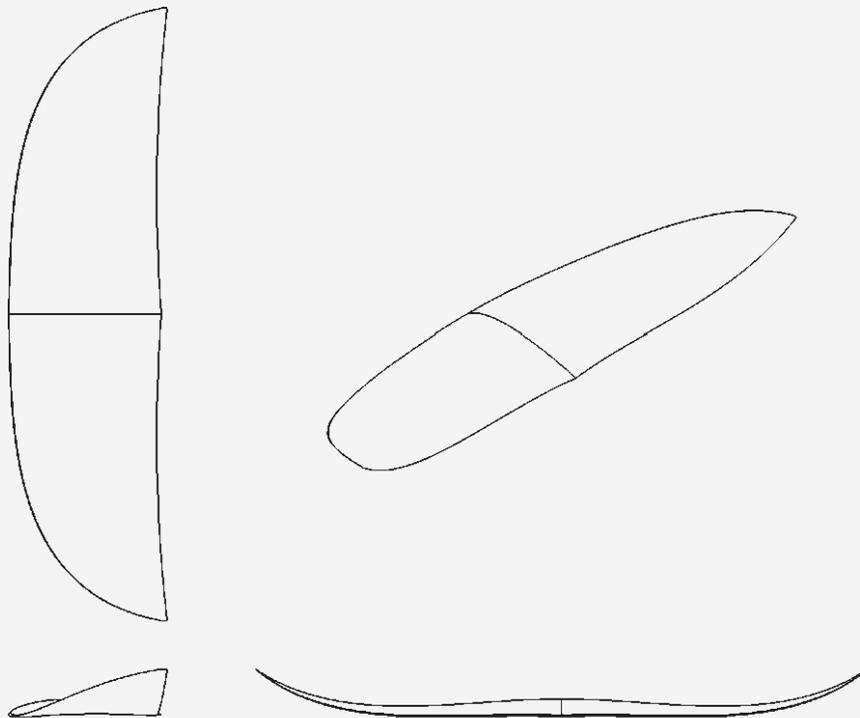
Concept #1



Concept #2



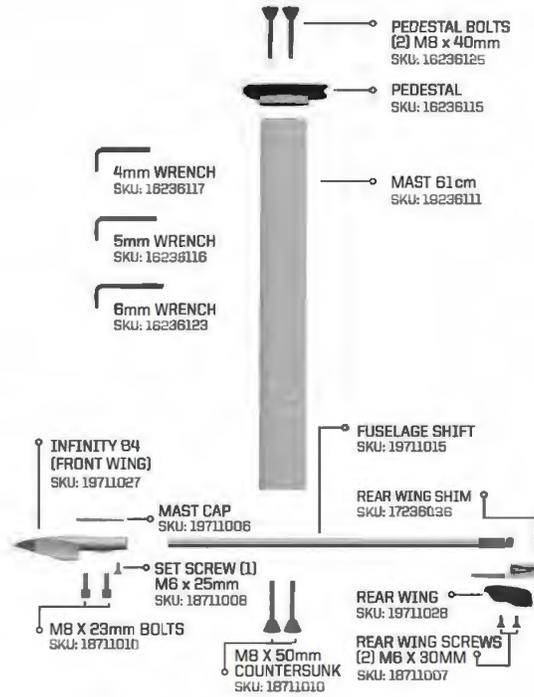
Concept #3



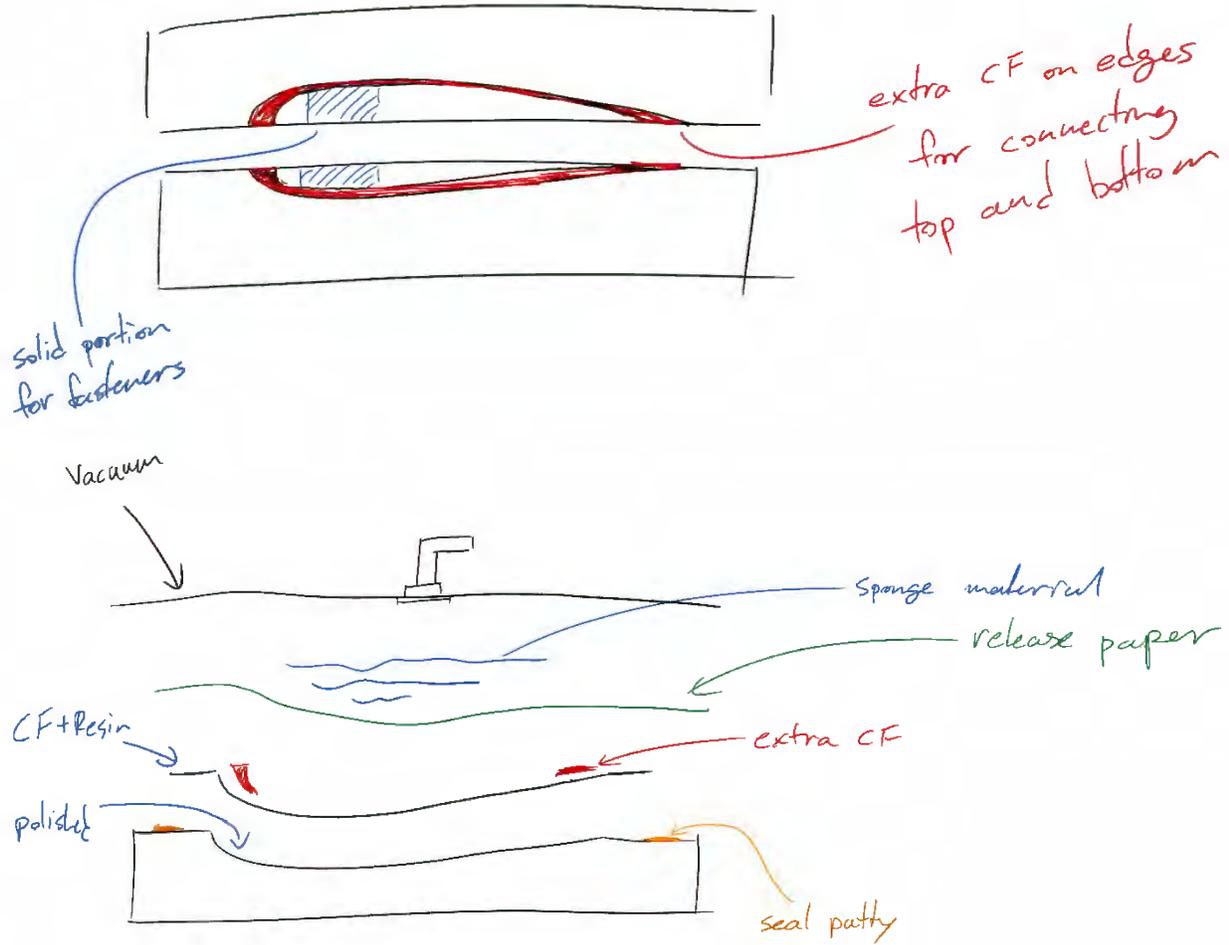
Full Mast and Fuselage Assembly



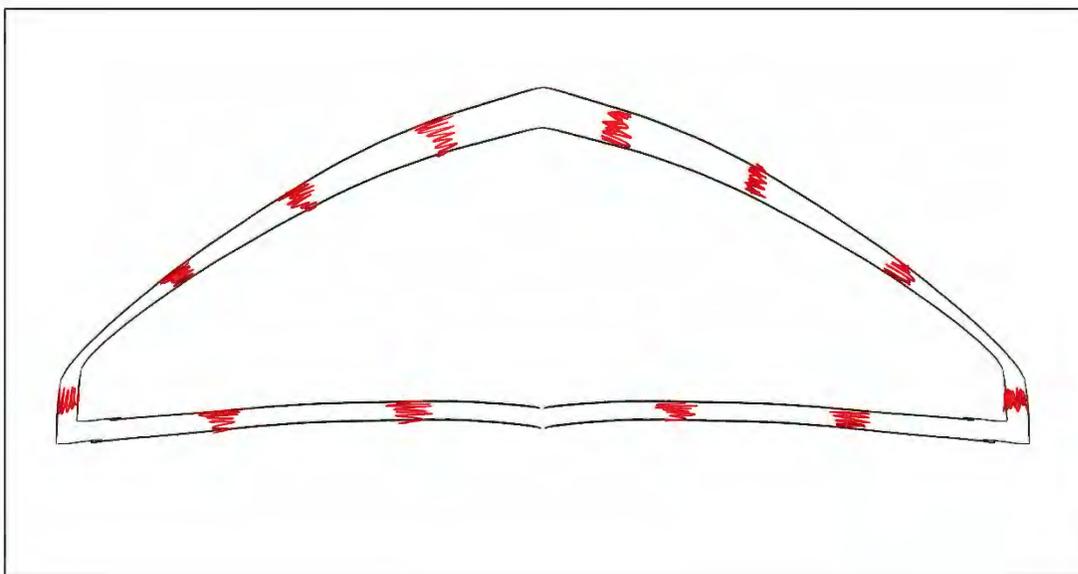
Manufacturing



Negative CF layup



Sold Wood CNC with tabs



Cost and schedule

Item	Cost
Paddleboard 7'3"	\$1,000.00
Mast 24"	\$100.00
Attachment System	\$100.00
Fuselage (Square bar stock)	\$20.00
Total Cost	\$1,220.00

Risk

- CNC wood machine not being available
Mitigation: Use 3D printer for core manufacturing

- Issues with carbon fiber layup
 - o Not properly conforming to shape of core
Mitigation: Use vacuum bagging process

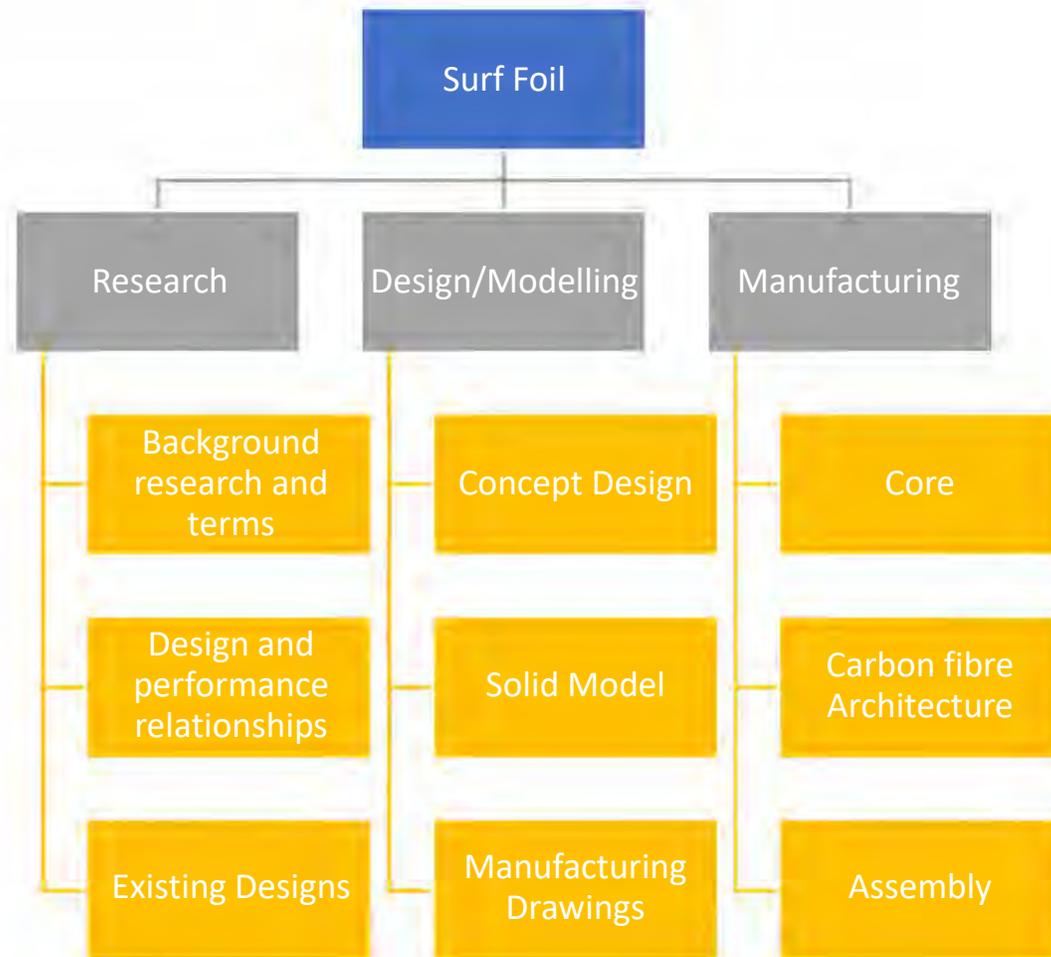
Appendix E Milestone Schedule

Deliverable Number	Deliverables Due	Date
1	Research Report	November 30, 2018
2	Conceptual Drawings	December 7, 2018
3	Solid CAD Model	December 29, 2018
4	Manufacturing Drawings	January 13, 2019
5	Design Review	February 15, 2019
6	Assembled Prototype	April 14, 2019

Appendix F Technical Requirements

Pitch Stability
Yaw Stability
Roll Stability
Max Operational Velocity
Min Operational Velocity
Lift to Speed Ratio
Lift to Drag Ratio
Maneuverability
Buoyancy
Max Operational Weight of User

Appendix G Work Breakdown Structure



Appendix H Responsibility Assignment Matrix

RACI Chart	Person		
Activity	Brian	Robin	Brandon
Background Research	A	R	R
Design and Performance Relationships	R	R	A
Existing Designs	R	A	R
Concept Drawings	R	A	C
Solid Model	R	A	C
Manufacturing Drawing	A	R	C
Core	R	A	R
Carbon Fibre Architecture	C	A	R
Assembly	A	R	R

Appendix I Gantt Chart

