Hydrofoil Design and Analysis

Introduction

Hydrofoils have been in use since the 1900s, mainly used for medium size to large boats. The appeal of a hydrofoil is the significant increase in efficiency as a result of the reduction in hydrodynamic drag. Today, hydrofoils have gained a lot of popularity in the water sports industry. Hydrofoils allow surfers to surf small waves with a smoother ride. The main pitfall of hydrofoils in this industry is their cost and their lack of longevity. The aim of this paper is to design a hydrofoil for surfing applications with an emphasis on ease of manufacturing.

Design Requirements

The aim of the design is to create a surfing hydrofoil. This design will focus on the hydrofoil geometry and optimize the rider experience. The analysis will focus on the hydrodynamic and structural capability, with an emphasis on the ease of manufacturing throughout. The design constraints listed below were formed from previous experience with hydrofoils.

Design Objectives

- The Foil must be able to lift a 200 lb person at a surfing speed of 12 mph.
- The Foil must be dynamically stable.
- The Foil structure must have a FOS of 2.0 for extreme riding conditions.
- The Foil must be under 50 lbs.
- All parts should be able to be manufactured with common equipment of machines at the University of Florida.
- The material cost should remain under $400.
- The Foil must have swappable components for future work.
- The Foil must be designed for beginner riders.

Current Designs

There is a wide range of hydrofoil designs in use today. Due to the large variance in uses, a lot of the designs may look different, but all have the same key features. It is first useful to examine these key features.

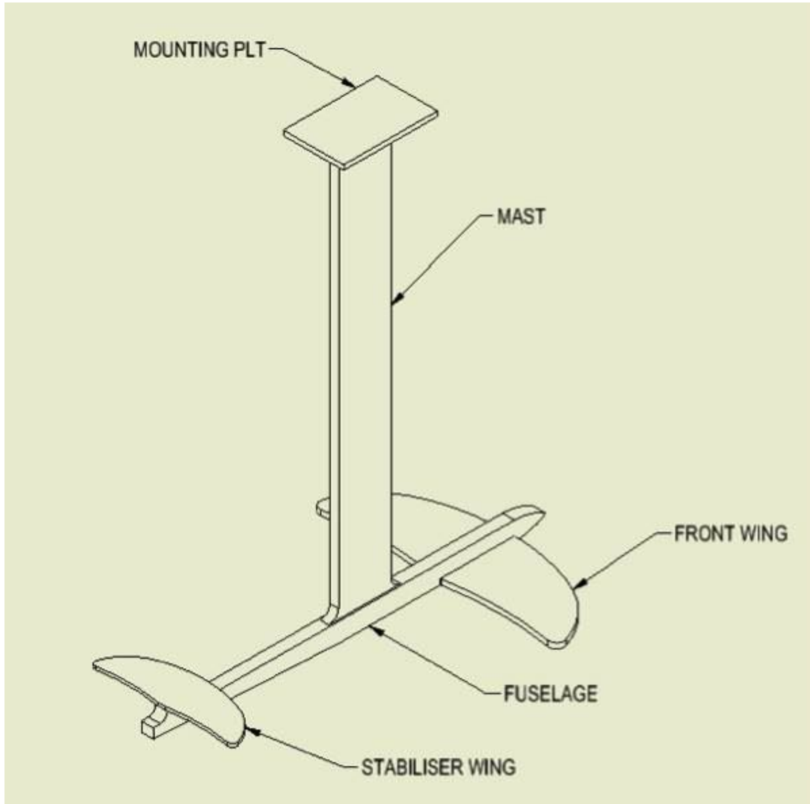


Fig. 1. Hydrofoil key features.

These key features can be compared with some of the most popular designs on the market. The comparison focuses on the main wing and fuselage, as these features show the greatest variance between designs.

Table I: Summary of Key Features of Current Designs

Foil Name	Wing Area (m^2)	Wing Span (m)	Aspect Ratio	Mast Length (m)	Fuselage Length (m)	Material
Phantom Carbon [1]	0.10 - 0.18	0.80 - 1.10	6.0	0.45 - 0.95	0.33-0.41	Pre-Preg CF
Ride Engine Futura [2]	0.21	0.84	3.3	0.71	0.61	CF/ Aluminum Mast
Slingshot Wake Foil [3]	0.08 - .21	0.60 - 0.70	3.2-5.0	0.50 - 0.92	0.60	CF/Aluminum

Fig. 2. Phantom Carbon Slingshot Wake Foil Ride Engine Futura

The sources listed above are some of the leading companies selling hydrofoils. Each product has a range of sizes to fit the needs of the buyer. The main differences in the hydrofoils depend on the weight of the rider and the use case for each hydrofoil.

The weight of the rider determines how big the front wing will be, as expected, as a bigger wing is needed to lift a larger rider. The previous designs indicate a wing area of 0.10 -0.22 m^2, with an aspect ratio of 3.0-6.0. As stated in the design objectives, this foil will need to lift a 200 lb rider plus the weight of the foil, which will put the wing area around at the high end of the expected range.

The type of riding also influences the design of the hydrofoil. As stated in the design objectives, the design should accommodate beginner riders at lower speeds. This means that a larger wing with a low aspect ratio is preferred, along with a large stabilizer.

Conceptual Design

The preliminary design will look at each component of the hydrofoil and generalize the shape/features. A simple analysis will be done for each component before moving into a more substantiated analysis in the preliminary design.

Main Wing

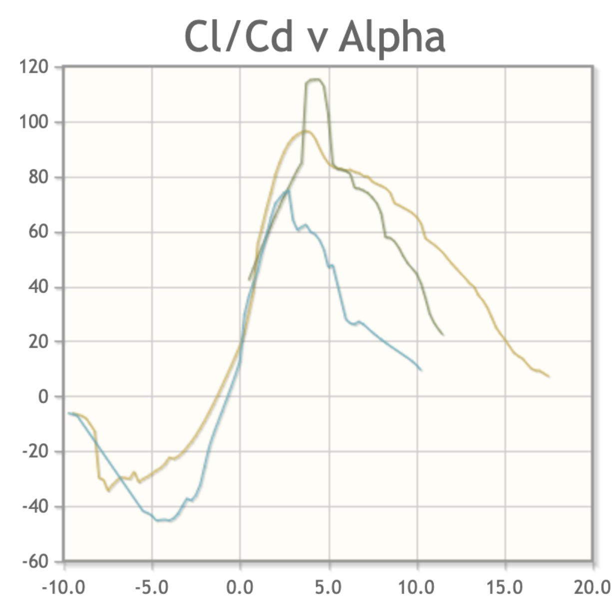
The main wing is the foundation of the hydrofoil. This is where most of the lift is produced and where most of the hydrodynamic analysis will be done. The first step is to estimate the Reynolds number which the hydrofoil will be operating. Using the design point of 12 mph and a characteristic length between 0.1-0.25 m, the Reynolds number is between 520000 - 1300000, which can fall into the same category as a light airplane.

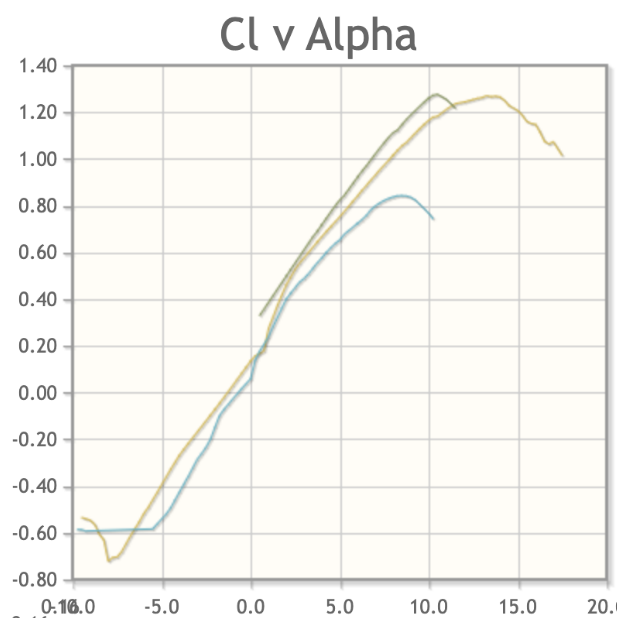
The next step is to pick an airfoil. This airfoil needs to provide significant lift at low angles of attack because the rider should not be pitched upward significantly during riding. A target $0 < \alpha < 5°$ is designated as acceptable riding conditions. The ideal condition is a 2° angle of attack. A cambered airfoil is better for this design. With an emphasis on structural safety and durability, the airfoil needs to be optimized to produce the least drag possible. Specifically, since the foil will be in the water, the drag will be ~800x more than it would be in the air. With these 2 design points, the ideal airfoil is less than 10% thickness and with a camber between 1-4%. Three airfoils that meet these design requirements are the NACA M11, NACA M13, and the Eppler 874. These airfoils were analyzed in XFOIL at a Reynolds number of 1,000,000 to get the airfoil characteristics.

Table 2: Airfoil Comparison

Airfoil	% Thickness	% Camber	C_L @ $\alpha = 2°$
NACA M11	8.2%	1.9%	0.31
NACA M13	6.2%	3.8%	0.50
Eppler 874	7.9%	0.9%	0.28

These airfoils can also be compared using XFOIL at a Reynolds number of 1,000,000. The results of the comparison can be seen below.





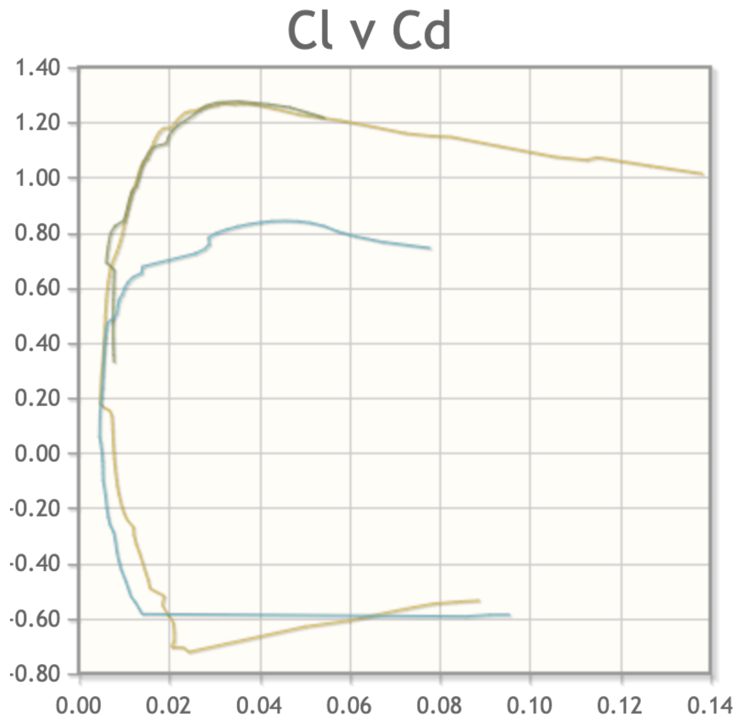


Fig. 3. Airfoil comparison. M11 - Yellow, M13 -Green, Eppler 874 - Blue

As these plots show, the Eppler 874 has generally a much lower efficiency ($\frac{Cl}{Cd}$) as compared to the other airfoils. This rules out the Eppler 874 as a viable option because there would be more drag at the required lift condition compared to the other foils. The NACA M11 and M13 show very similar characteristics. The M13 has double the amount of camber of the M11, which increases the lift at α = 0°. This large camber in the M13 would cause problems with probable manufacturing technique, CNC milling. The NACA M11 airfoil will be used for this design.

The next step is to determine the wing area. The wing area will include no factor of safety due to the nature of the project. The foil is under constantly changing conditions, so a factor of safety would do little in comparison to the changing conditions.

From a conceptual design perspective, the lift produced depends on the 2 non-constants in the basic lift equation, velocity, and the coefficient of lift. We are considering the main wing lifting a 200 lb person with an additional 50 lbs for the entire hydrofoil. Here we are assuming no lift is created by the horizontal stabilizer.

$$Weight\ =\ Lift$$
$$Wing\ Area\ =\ \frac{Lift}{.5 * \rho * v^2 * c_L}$$

The density of seawater is 1024 $\frac{kg}{m^3}$. The velocity has a viable range of 2 - 7 $\frac{m}{s}$. The coefficient of lift has a viable range of 0.1 - 0.8. The wing area as a function of these variables can be seen below.

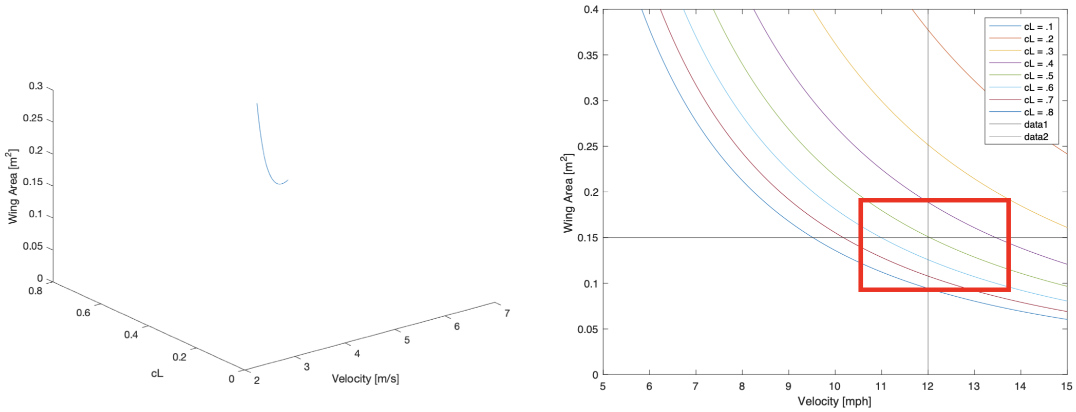


Fig. 4. Wing area calculation. The calculation is done based on varying speed and C_L.

There is a range of conditions that meet the design requirement (seen in the red box above). The coefficient of lift range that meets the design objective is $c_L > 0.3$. As seen in previous research, the max wing area is around 0.2 m^2, which is what can be seen here as a reasonable value. The lowest possible wing area that meets design objectives will be chosen to reduce the total drag as much as possible. With this information, a wing area can be nominally chosen to be 0.15 m^2 based on the expected c_L from the M11 airfoil. To meet design objectives, the wing needs to have a c_L of 0.4 at cruise conditions. This is very close to the expected c_L at $\alpha = 2$, which is an ideal angle for the rider.

The next step is to decide on an aspect ratio for the wing. Conventional wisdom says the higher the aspect ratio, the more efficient the wing is and has a higher minimum speed to lift. The smaller the aspect ratio, the more stable the wing is. A higher aspect ratio results in a lower induced drag from basic induced drag theory. For this design, it is best to choose a mid-range aspect ratio as either end of the aspect ratio spectrum conflicts with a design objective. The wing is designed for beginners (very stable) and designed for minimum drag (structural emphasis). From the current design research, aspect ratios vary from 3.0 - 8.0. An aspect ratio of 5.0 provides a balance for stability and efficiency, This leads to a span of 0.87 m and an average chord of 0.17 m.

Many current designs have a prominent front-to-back wing sweep. In a previous study [4], a forward or backward sweep was found to reduce form drag in hydrofoils, compared to unswept hydrofoils. This was due to flow separation mitigation. For this design, the hydrofoil will have a leading edge sweep angle of 15 degrees. The wing will have no twist as there are no control surfaces on the wing.

A taper ratio will be used to help eliminate induced drag on the wing. From induced drag theory, an elliptical wing results in the lowest induced drag. For ease of manufacturing and design, a taper ratio of 0.5 will be used to simulate a nearly elliptical shape.

$$C_{d,i} = \frac{C_L^2}{\pi AR e}$$

Where e is the Oswald efficiency factor and AR is the aspect ratio. This leads to a root chord of 0.28 m and a tip chord of 0.07 m.

There will be no incidence angle on the wing. While this would help rider comfort, the manufacturing technique for the wing, CNC milling, does not yield itself well to an incidence angle. Many current designs have a slight degree of anhedral, as to keep the wingtips in the water if the wing reaches the surface, but for ease of manufacturing, the wing will have no anhedral or dihedral. The wing is going to be CNC cut out of thin material, so adding anhedral or increasing the thickness of the material and therefore the cost.

The wing tips will be rounded to avoid potential injury if the wing collides with the rider. While this is not ideal for wing efficiency, it is necessary for safety.

With all of the wing designs chosen, the wing can be modeled. The decisions above will be optimized in the detailed design, but the preliminary design outlines the general geometry of the wing based on design objectives. The wing was modeled in OpenVSP.

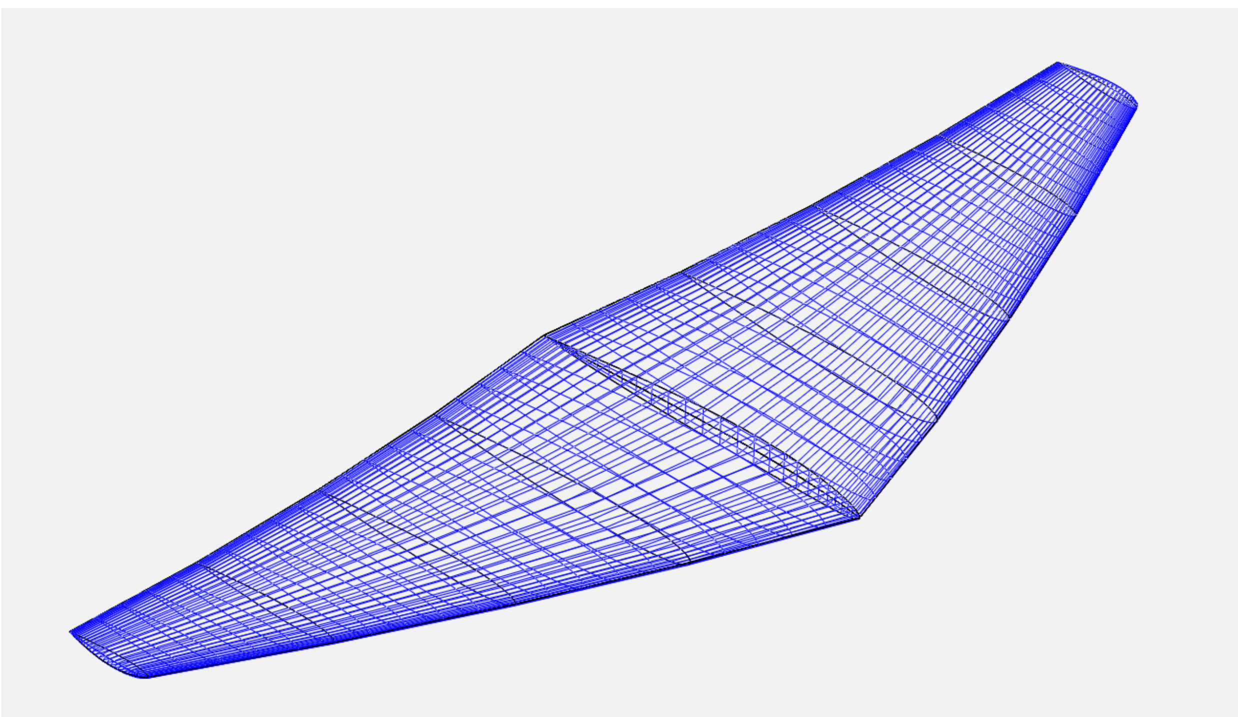


Fig. 5. Front wing modeled in OpenVSP.

This wing can be analyzed in openVSP using VSPAero. The simulation was performed at Re = 1,000,000 and from α = 1:10. VSPAero uses the vortex lattice method to perform the simulation.

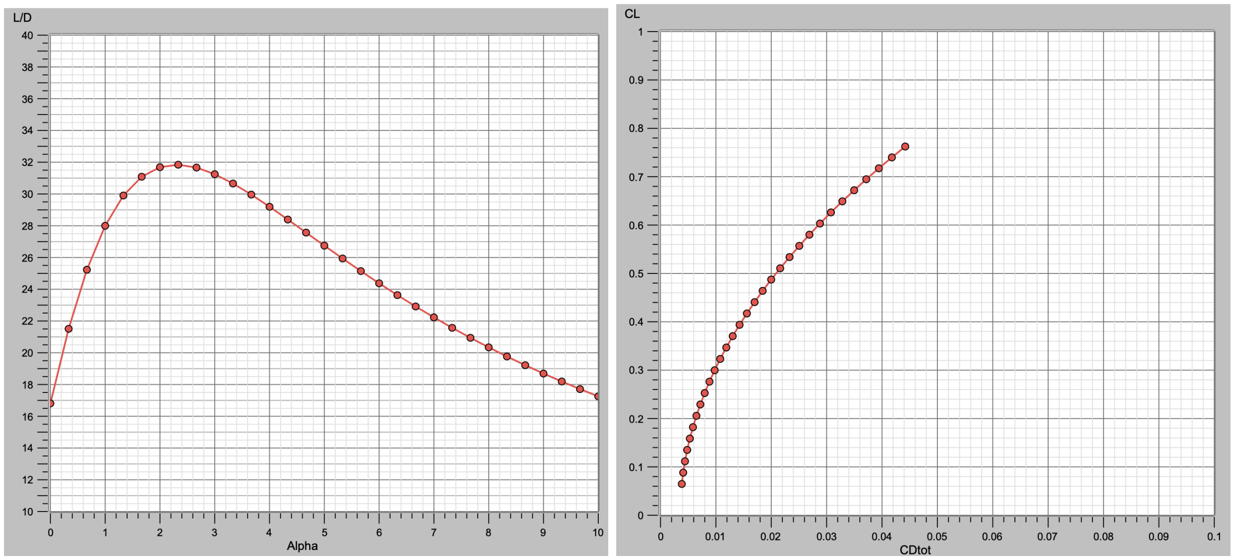


Fig. 6. Vortex lattice simulation of the front wing.

The results show similar results seen above in the airfoil analysis. There is a max L/D of 32 at $\alpha = 2.4$ degrees. CDtot is the summation of the parasite and induced drag. This can be used in the drag analysis. These results should be taken with a grain of salt as the results presented heavily depend on the tessellation of the wing. All shown results converged.

Stabilizer

The horizontal stabilizer will be a symmetric airfoil, a NACA0010. This is a common choice for stabilizers as it produces very little drag. The size of the stabilizer is dependent on the length of the fuselage and the position of the mast and main wing. To solve this, we can assume a relationship between the lift of the main wing and the stabilizer.

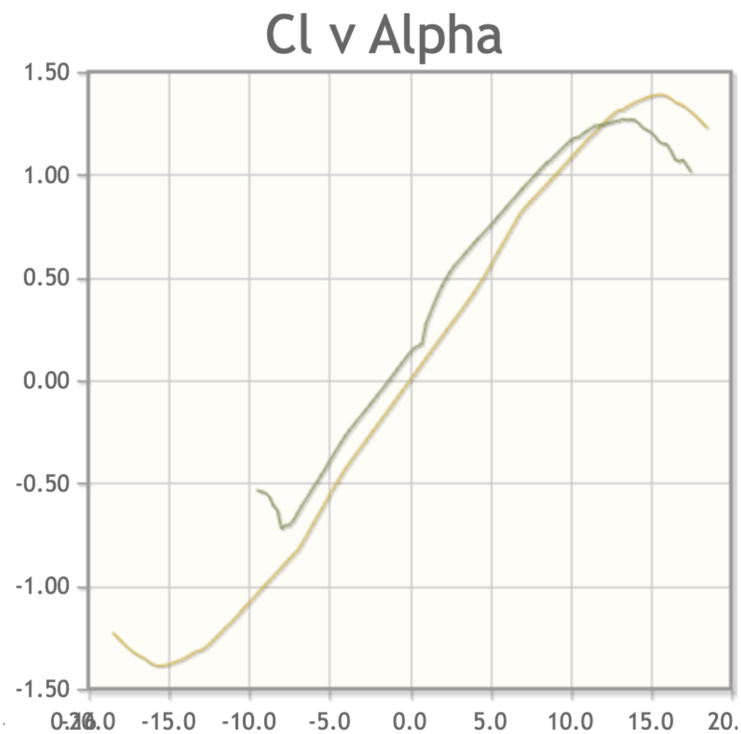


Fig. 7. Horizontal stabilizer airfoil comparison. M11 - Green, NACA0010 - Beige

Examining the coefficient of lift plots we can assume the stabilizer will have a C_L of $.9C_L$ the C_L of the main wing, At the cruise condition, or trim, there needs to be a net zero moment at the location of the mast. In this way, the lift force is directly through the mast and into the board. While this will be the case for surfing, another situation requires the center of lift of the system to be forward of the mast to counteract the moment created by being pulled by a rope. This means the best option is to have multiple mast mounting locations to optimize for the riding situation.

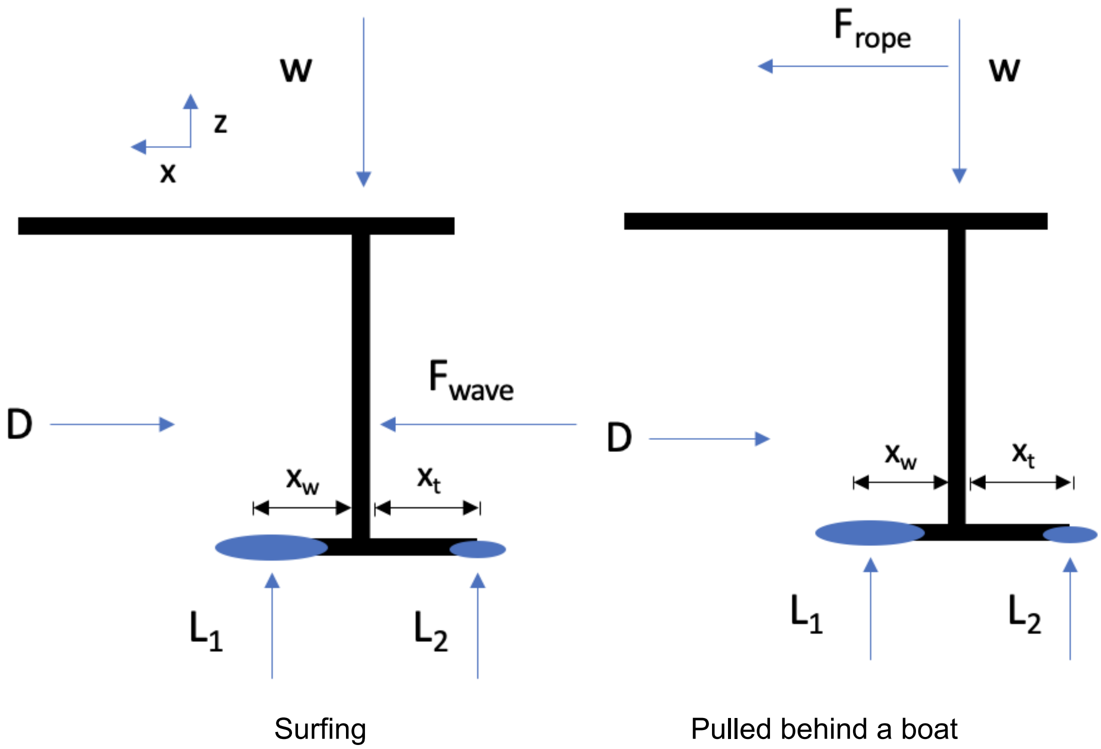


Fig. 8. Free body diagram of the hydrofoil.

For the initial design, the moments can be summed around the mast. This is assumed to be the center of gravity. The distance from the aerodynamic center of the main wing is defined as x_w and the distance from the aerodynamic center of the stabilizer to the mast is defined as x_t. This analysis will be based on the surfing situation, and assume that the driving force of foil, the force from the wave, acts at the same z location. The forces on the foil from this wave are very complex, so this assumption simplifies the analysis for design.

$$\Sigma M_y = 0 = x_w \widehat{x} \times L_1 \hat{z} - x_t \widehat{x} \times L_2 \hat{z}$$

$$x_w \widehat{x} \times L_1 \hat{z} = x_t \widehat{x} \times L_2 \hat{z}$$

$$x_w L_1 = x_t L_2 \hat{z}$$

$$x_w \frac{1}{2} \rho v^2 c_{L_1} A_w = x_t \frac{1}{2} \rho v^2 c_{L_2} A_t$$

$$x_w \frac{1}{2} \rho v^2 c_L A_w = x_t \frac{1}{2} \rho v^2 (0.9 c_L) A_t$$

$$x_w c_L A_w = x_t (0.9 c_L) A_t$$

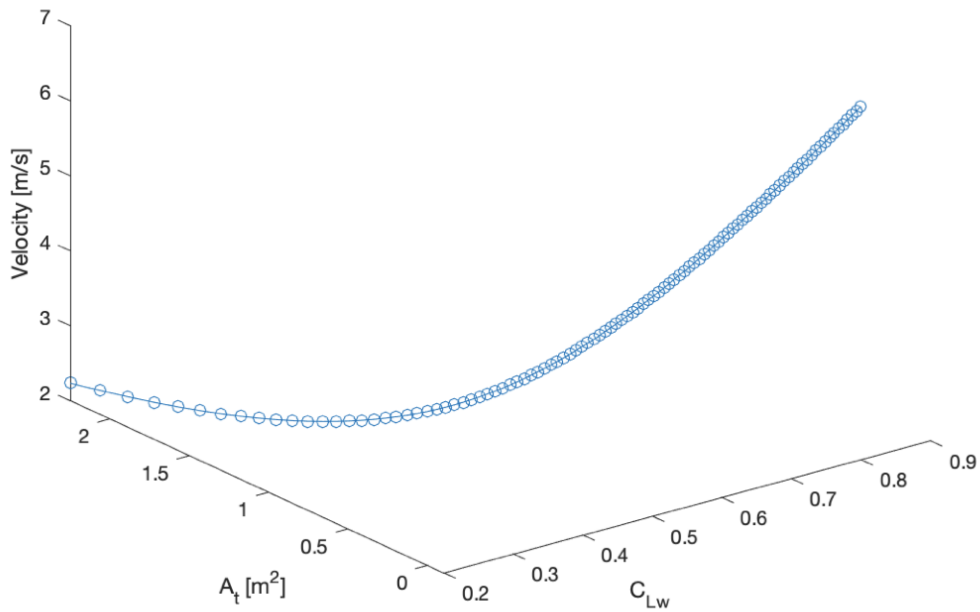
$$1.11\, x_w A_w = x_t A_t$$

$$0.156 x_w = x_t A_t$$

We can also sum the forces for the system to obtain another equation.

$$\Sigma F_y = 0 = -W + L_w + L_t$$
$$W = \frac{1}{2}\rho v^2 (c_{L}A_w + .9c_{L}A_t)$$

The sizing of the stabilizer is highly sensitive to the coefficient of the lift of the main wing and the speed. A 3D plot of these variables can be seen below.



Examining A_t during most operating conditions, v = 8 - 15 mph and $C_{L,w}$ = 0.1-0.5, the area of the tail is between 0.03 m^2 and 0.08 m^2. An a speed of 5.5 m/s and a $C_{L,w}$ = 0.37, the resulting stabilizer area becomes:

$$A_t = 0.05\, m^2$$

This stabilizer wing area is for the design condition at cruise. This is a valid assumption for preliminary design because the majority of the operating conditions will be near cruise conditions.

Then, we can solve for a ratio of x_t to x_w.

$$\frac{x_t}{x_w} = 1.87$$

Now that the stabilizer wing area was found, the wing can be characterized. The stabilizer will be a simple design with no sweep or dihedral. The wing will have an aspect ratio of

4.0. Along with this, the wing will have a taper of 0.7 to decrease some of the induced drag on the wing. Since the wing creates significantly less lift than the main wing, the induced drag on this wing can be neglected. With these design choices, the stabilizer will have a span of 0.45 m with an average chord of 0.11 m. The stabilizer can then be modeled in OpenVSP.

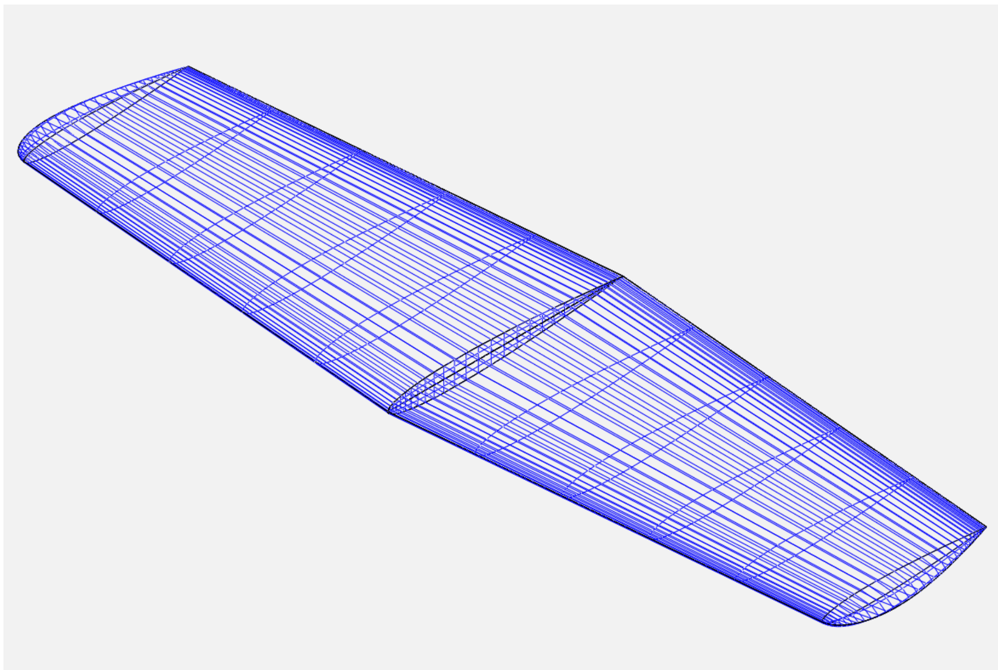


Fig. 9. Horizontal stabilizer modeling in OpenVSP.

Fuselage

The fuselage will serve as the mounting point for the main wing, mast, and stabilizer. This main design criterion for the fuselage is to provide various mounting positions for the mast, be easily assembled, be as hydrodynamic as possible, and have a safety factor of 2.0 for its structure.

To accommodate multiple mounting positions, the fuselage will have 5 mounting holes, evening spaced. Assuming that the mast will be mounted with 2 M8 bolts (industry standard), this allows for 4 different mounting positions. This simple solution will allow for experimentation on which mast position allows for the best ride.

To accommodate for easy assembly, the fuselage will use as few bolts as possible to connect the pieces together. There will be 2 bolts for the mast, two bolts for the horizontal stabilizer, and 2 bolts for the main wing. This should allow for easy assembly and simplified storage of the hydrofoil.

The mast will be as hydrodynamic as possible. This is characterized as minimizing the frontal cross-sectional area. Along with designing for the smallest fuselage radius, the fuselage will also be attached slightly below the top of the wing, to minimize this area.

From the longitudinal static stability analysis the ratio of $\frac{x_t}{x_w}$ was found. This can be used to determine the fuselage length. For the baseline fuselage length, industry-standard fuselage lengths along with the ratio above will fully define the fuselage. A fuselage length of 0.71m is standard. This yields $x_t = 0.46\,m$ and $x_w = 0.25\,m$.

The cross-section of the fuselage depends on the structural analysis. The rest of the fuselage will be fully defined in that section. The material of the fuselage can be chosen in this section. The material will be chosen via an Ashby chart. For a simply supported beam, with a square cross-section (assumed), the maximum deflection can be calculated as

$$y = \frac{PL^3}{48EI}$$

$$I = \frac{1}{12}a^4$$

Then, the mass of the fuselage can be defined as

$$mass = a^2L\rho$$

Solving for a^2 and substituting into the mass equation yields:

$$mass_{min} = \frac{2\sqrt{y}\sqrt{E}}{\sqrt{p}\sqrt[5]{L}\rho}$$

For the minimal mass, we want to maximize $\frac{\sqrt{E}}{\rho}$.

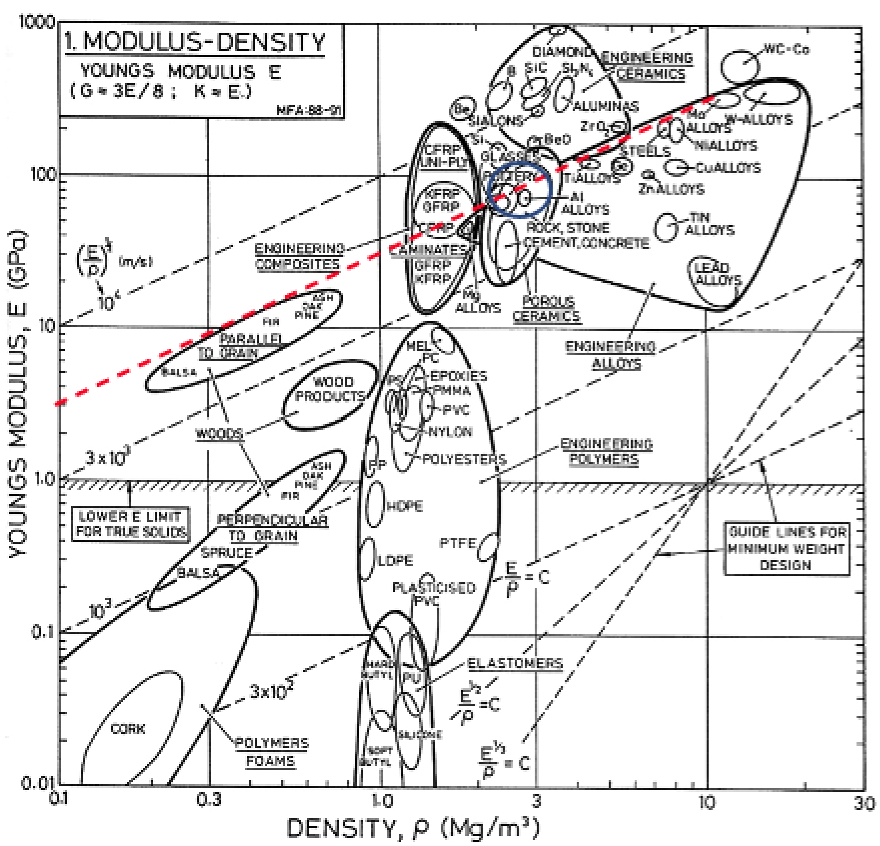


Fig. 10. Ashby Density vs. E chart [5].

Moving along the highest $\frac{\sqrt{E}}{\rho}$ = constant slope line in the Ashby chart, E vs. ρ, the best material to choose is unidirectional carbon fiber reinforced plastic. As the fuselage will have many mounting holes that need to be tapped, carbon fiber is not the best choice for manufacturing the fuselage. The next materials along this line are aluminum alloys, titanium alloys, and steel. Aluminum alloys are by far the easiest material to obtain, so this is the material chosen for the fuselage. Specifically 6061 aluminum will be used for this project. This has a yield strength of 241 MPa and a modulus of E = 69 GPa.

Mast

The mast determines how far the rider is above the water. There are multiple effects the mast height has on the hydrofoil. First, the taller the mast, the higher a person is when they fall off the foil. For this reason, a shorter mast for beginners is recommended. But, a taller mast allows the rider to cut through taller waves. When a rider is being pulled with a rope, the mast also determines the moment created from the rope pull.

The mast used will be a standard mast used in industry. This will ensure a standard connection to a board. The mast will be 24” long to ensure short falls on the foil. The mast has 2 M8 threaded holes on the top and bottom for mounting. The mast can be seen below.

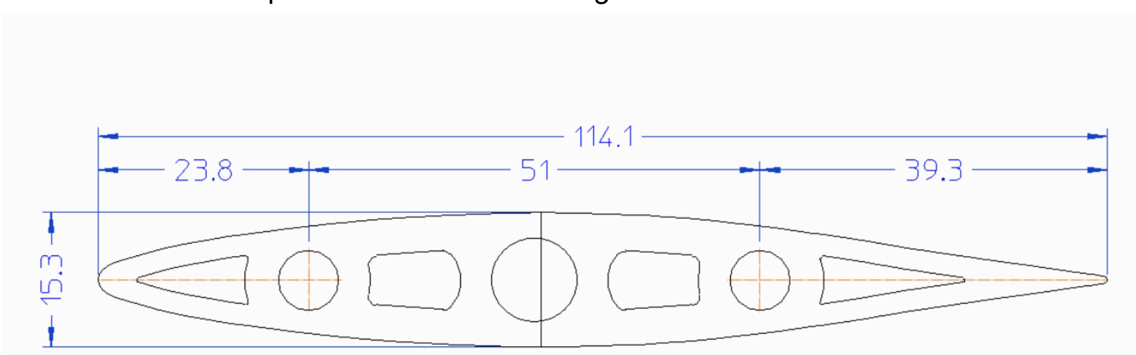


Fig. 11. Industry standard mast cross section. 24” in length and 2 M8 mounting holes.

Drag Analysis

For the conceptual design, a simple drag analysis will be done in openVSP. Each component of the hydrofoil will be analyzed to get a specific C_D, Then, the total drag will be a summation of the drag from each component. The interaction between the elements in the flow will be assumed negligible. The fuselage drag will also be assumed to be negligible as there is little frontal area in the flow. VSPAero was used to calculate both parasite and induced drag. The summation of these drag coefficients will be the total C_D.

$$C_D = C_{D_0} + C_{D_i}$$

$$D = .5\rho v^2 A(C_{D,wing} + C_{D,stabilizer} + C_{D,mast})$$

The area chosen here is the wing area, as that is what is used by openVSP. At a velocity of 5.5 m/s and a $\alpha = 3$ degrees, the drag force is equal to 55 N.

$$D = .5\rho v^2 A(0.009 + 0.007 + 0.0035) = 55\,N$$

This is a very low drag force. The C_D values simulated from VSPAero were very low. This is a rough estimate of the drag force and further analysis will be done to substantiate this.

Structural Analysis

Fuselage

The fuselage will be the main focus of the structural analysis, as that is where the highest stress concentration is. The fuselage can be analyzed as a simply supported plate.

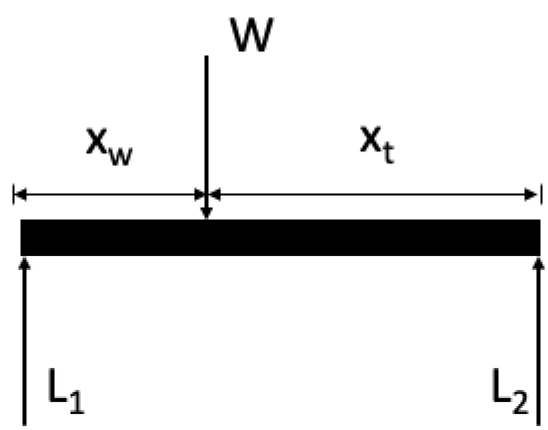


Fig. 11. Fuselage free body diagram.

This yields a maximum shear and moment as follows.

$$V_{max} = \frac{Wx_w x_t}{x_w + x_t} = 725\,N$$

$$M_{max} = \frac{Wx_w x_t}{x_w + x_t} = 179\,N - m$$

These then can be used to calculate the minimum area/radius for the fuselage, including the FOS. The transverse shear stress can be calculated for both a circular and rectangular cross-section.

$$\tau_{max} = \frac{VQ}{It} = \frac{V\bar{y}A'}{\frac{1}{12}bh^3 b} = 1.5\frac{V}{A}$$

$$\tau_{max} = \frac{VQ}{It} = \frac{8V}{3\pi r^2}$$

The normal stress due to the moment can also be calculated.

$$\sigma_{max} = \frac{My}{I} = \frac{4M}{\pi r^3}$$
$$\sigma_{max} = \frac{My}{I} = \frac{6M}{bh^2}$$

We know the yield strength of 6061 Aluminum and the factor of safety, so this can be used to calculate the fuselage geometry.

$$FOS = \frac{\sigma_{allow}}{\sigma_{max}} = \frac{\sigma_y}{\sigma_{max}}$$
$$\sigma_{max} = \frac{\sigma_y}{FOS} = 120.5$$

Solving for the radius in the above equations,

$$r = \frac{2\sqrt{2}\sqrt{V}}{\sqrt{3\tau_{max}\pi}} = 0.1''$$
$$r = \sqrt[3]{\frac{4M}{\pi\sigma_{max}}} = 0.52''$$

From that analysis, the bending moment causes much greater stress on the fuselage. For an optimal design, the fuselage needs to be rectangular, to distribute the material farther away from the neutral axis.

$$A = \frac{1.5\,V}{\tau_{max}}$$
$$Ah = \frac{6M}{\sigma_{max}}$$

This can be solved for various ratios of the base to height. The solutions can be seen below.

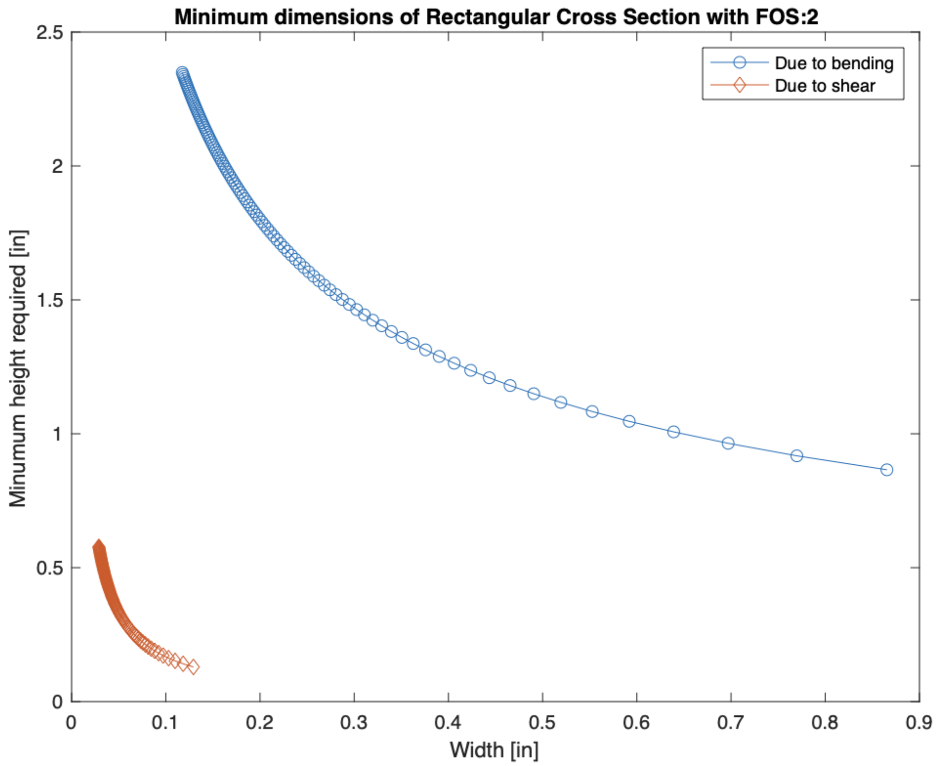


Fig. 12. Fuselage structural optimization for a rectangular cross-section.

Once again, the bedding moment dominates the stress intensity. The minimum dimensions for a square cross-section would be 0.87” x 0.87”. This is less than the minimum 1” diameter for the circular cross-section. This makes sense as more material is further from the neutral axis with the rectangular cross-section.

Using the industry standard mast, the fuselage needs to have at least 0.1” clearance on both sides when the mast is flat on the fuselage. Therefore, the fuselage needs to be 0.8 “ wide. Optimizing this with the analysis above, the fuselage has dimensions of 0.80” x 0.91”.

Since the maximum stress occurs at the mast, the fuselage cross-sectional area can become smaller towards the stabilizer, but due to manufacturing, the fuselage cross-section will remain constant.

A ⅞” x 1” 6061 aluminum bar stock will be used for the fuselage. This is due to the easy availability of the bar stock. This results in a FOS > 2.0.

Wing

The wing will be a wood core with a carbon fiber wrap. The loads will be more defined with the FEA analysis. For the conceptual design, the load distribution can be defined through VSPAERO.

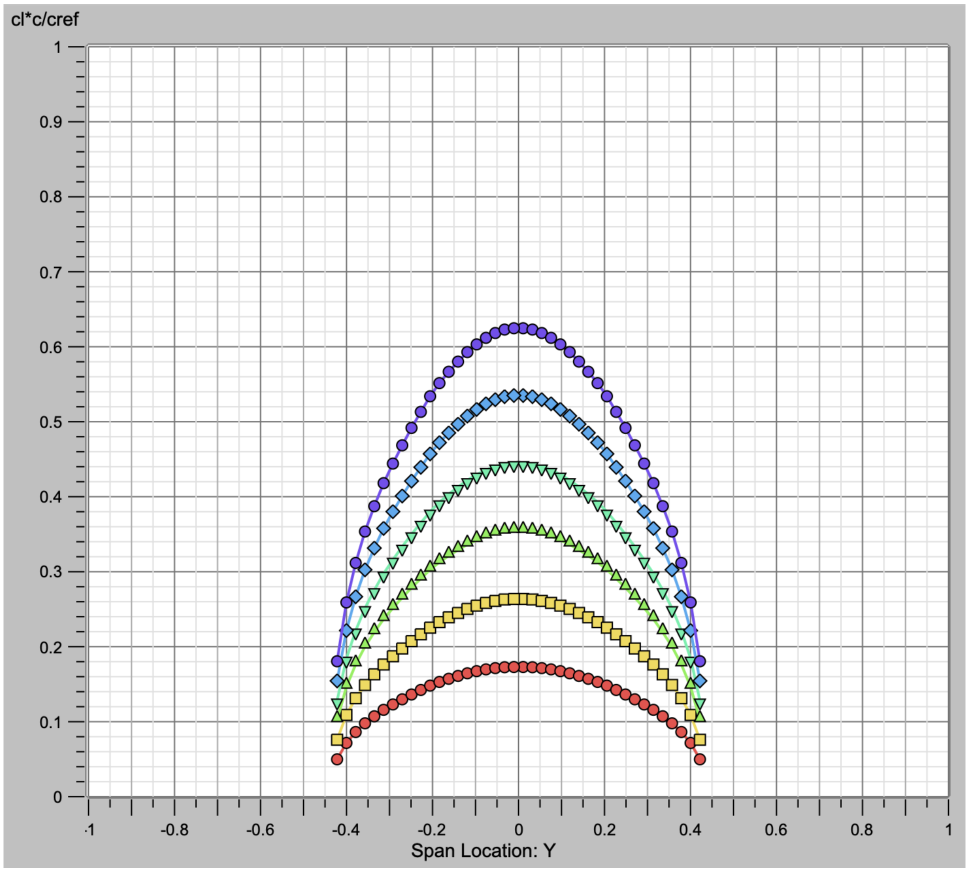


Fig. 13. Lift distribution per span over α = 1:10.

Buoyancy Force

In addition to the lift created by the wing, the buoyancy force from the wing needs to be analyzed. This may potentially affect the size of the wing if the buoyancy force is significant.

$$B = \rho V g$$

$$B = \rho (V_{wing} + V_{stabilizer} + V_{fuselage} + .5V_{mast})\, g$$

$$B = 28.05\ N$$

Conceptual Design Summary

The conceptual design completely defined all geometry for the hydrofoil. This geometry was then modeled in SOLIDWORKS. The model can be seen below.

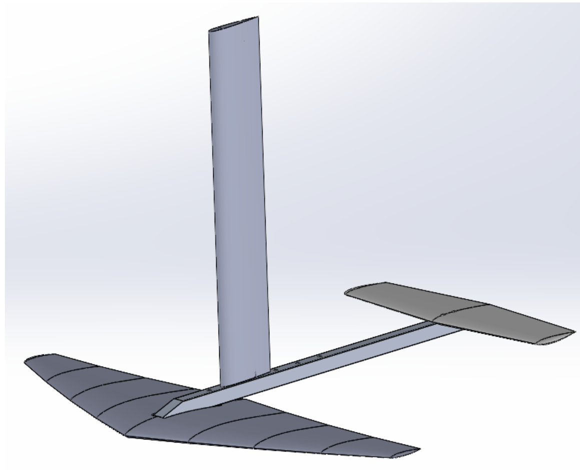


Fig. 14. Conceptual design assembled hydrofoil.

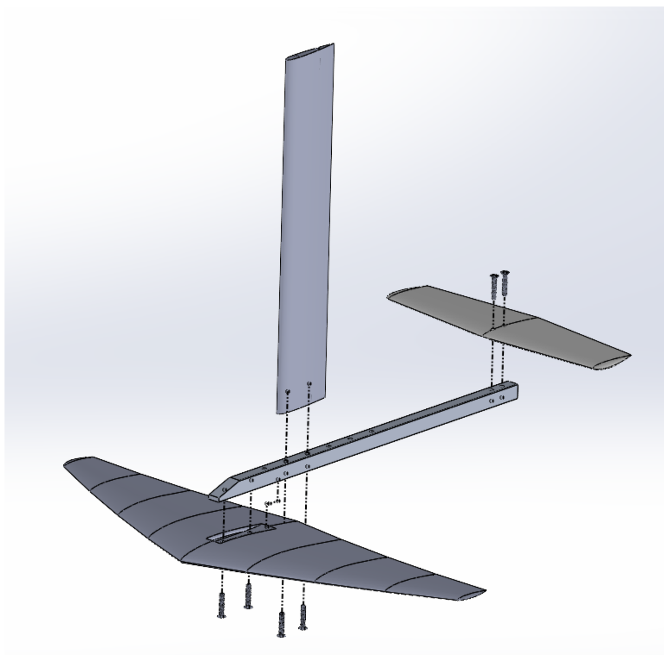


Fig. 15. Conceptual design exploded view of assembled hydrofoil.

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Appendix

Appendix A: Nomenclature

FOS	Factor of Safety		
CF	Carbon Fiber		