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FINAL REPORT

Hydrofoil Design and Manufacture For a Scaled Sailboat

by

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SMARTLAB is a research laboratory for scaled dynamic testing of new vehicles. This research laboratory was established by Professor N. Sarigul-Klijn in 1995 to conduct flight and ground testing of mobility systems.

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Contents

Table of Figures

Table of Tables

1 INTRODUCTION

As the demand for renewable energy sources increase, it is important to investigate the untapped energy markets. Wind energy is currently only harvested on land using windmills, however, the world is mostly covered in water. The idea behind the Energy Ship is to equip a sailboat with a hydro-kinetic turbine that will use the ocean wind energy to power an electrolyzer to harvest and store hydrogen.

A typical sailboat is limited in the speeds that it can achieve based on the current wind conditions and the drag of the hull. The addition of a hydro-kinetic turbine to a sailboat creates additional drag, resulting in less energy conversion. The addition of hydrofoils has the potential to improve stability and reduce the drag due to the sailboat hull and hydro-kinetic turbine in order to increase the sailboat speed to harvest more of the wind energy.

2 BACKGROUND INFORMATION

Hydrofoils are similar in design and purpose as airfoils used in airplanes. As the water moves past the hydrofoil, the shape forces the water to move faster above the foil and slower below. This decreases the pressure above the foil due to the increased velocity which generates lift. As this force lifts the boat out of the water, the drag generated by the hull of the boat decreases which, in turn, increases the speed (Yechout et al., n.d.).

As can be seen in Figure 1, there are two main different types of hydrofoils: surface piercing and fully submerged (Department of Defense, 1970). As the name states, surface piercing hydrofoils are partially submerged with part of the hydrofoil above water while the fully submerged hydrofoils are completely underwater.

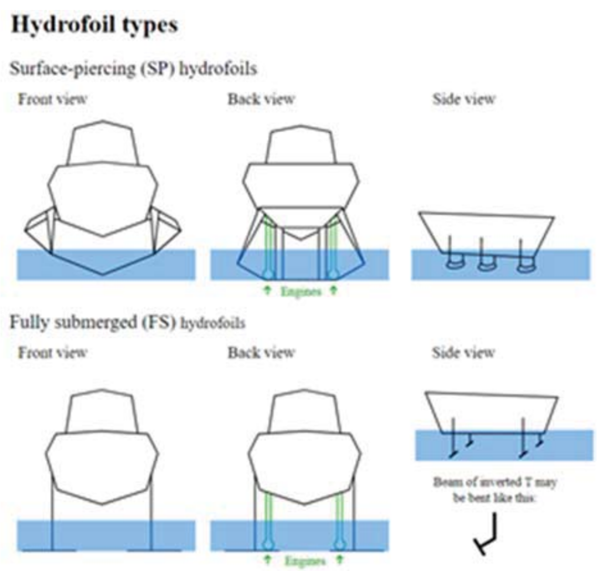


Figure 1: Surface piercing and full submerged hydrofoils (Hydrofoil Types, 2009).

The three distinct modes of sailing that will be considered in this project are displacement, semi-foiling, and full-foiling. The displacement mode refers to the normal sailing of a boat without hydrofoils. Semi-foiling, which can be seen on the left in Figure 2, is when there is one hydrofoil lifting just the front of the boat. With the rear of the boat in the water, semi-foiling does not decrease the drag as much as full-foiling but provides more stability. Full-foiling, which can be seen on the right in Figure 2, is when there are hydrofoils on the front and back of the boat so that the entire boat is lifted out of the water. This mode allows the most substantial decrease in drag but also presents an inherent lack of stability (Penzba.co.uk, 2014).

Figure 2:Semi-foil on the left (Journee, 2002) and full-foil on the right (Heli-air.net, 2016).

3 DESIGN

3.1 PROJECT SPECIFICATIONS

A hydrofoil system was designed, manufactured, and installed on a remote-control LASER model sailboat to meet the following specifications provided by the client:

- The boat must operate in wind conditions of 6-10 knots (~7-11.2 mph)
- Hydrofoil system must be removable
- Boat must operate in semi and full-foiling modes
- Sailboat will be autonomous
- Test impact of hydro-kinetic turbine on velocity by simulating turbine with a 2" by 2" plate
- Budget of less than $1000

3.2 HYDROFOIL CONFIGURATION AND PROFILE

The V-shaped hydrofoil design was chosen for both the front and rear. A V-foil with constant chord has a larger lift/drag ratio for the anticipated lower speeds (Figure 3).

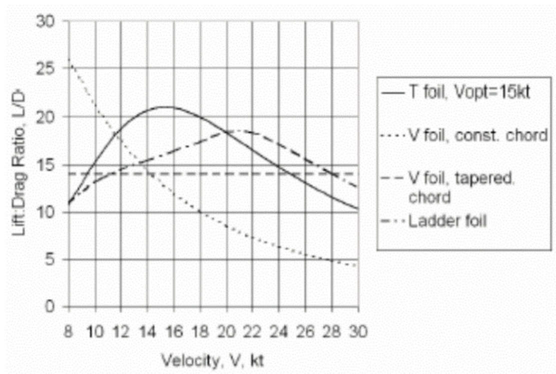


Figure 3: Lift/drag ratio for different hydrofoil shapes (Joyce et al.).

According to the Department of Defense Hydrofoil Handbook, surface piercing (V-shaped) hydrofoils also have more height and side stability than fully submerged (T-shaped) hydrofoils. In the V-foil configuration, as the boat lifts more out of the water, less of the foil is submerged which decreases lift and lowers the height while for T-shaped hydrofoils, the angle of attack must be varied to control the height stability (Biran, 2009). When the boat begins to lean, the amount of the V-shaped foil submerged on that side increases and the resulting increase in lift rights the boat. The V-foil configuration allowed for simplification in the design by eliminating the need for servo motors or Arduinos to control the angle of attack.

In addition to being specifically designed for hydrofoils, the Speer H105 profile was chosen because it maintains large coefficients of lift without cavitation and avoids laminar separation and ventilation when operating at low speeds and moderate angles of attack (Speer, 1999). The profile coordinates can be seen in Figure 4 and has a thickness that is 12.5% of the chord.

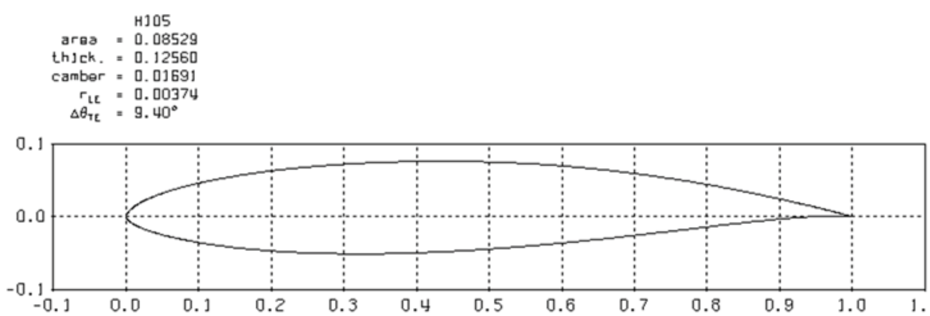


Figure 4: Speer H105 profile (Speer, 2001).

3.3 DIMENSION CALCULATIONS

The dimensions of the hydrofoils were calculated for front and rear foils of the same size. The entire RC laser boat weighed 7.75 lbs. and the mounting mechanism was found on SolidWorks to be 8 lbs. The take-off speed for a hydrofoiling boat can be approximated as half of the maximum velocity, 11.2 mph, which was calculated as 5.6 mph (Vellinga, 2005). The coefficient of lift for the H105 profile was taken as 0.4 (Speer, 2001). The coefficient of drag was calculated as the sum of the drag coefficient, 0.01, and the skin drag (Speer, 2001). Using Engineering Equation Solver, EES, a program was written to solve for the necessary span and chord length as well as the wetted span at take-off and maximum velocity (See Appendix A.3 for EES code). The additional weight of the autonomous control, 4 lbs., was used to calculate the adjusted forces and required velocities. The following tables summarize the results:

Table 1: Required dimensions for hydrofoil.

Hydrofoil	Chord	Length	Thickness
Front	2.5 in	12.5 in	0.35 in
Rear	2.5 in	12.5 in	0.35 in

Table 2: Calculated forces on hydrofoil.

Parameter	No Auto. Control	Auto. Control
Drag due to Foils at Maximum Velocity	0.7 lbf	0.87 lbf
Wind Force (10 knots)	2.21lbf	2.2 lbf
Hydrofoil Lift Required (per foil)	7.88 lbf	9.89 lbf
Total Coefficient of Drag	0.01766	0.01766
Take-off Velocity	5.6 mph	6.7 mph
Wetted Span at Take-off Velocity	17.45 in	17.45 in
Wetted Span at Maximum Velocity	4.36 in	5.46 in

The wetted span represents the projected length of hydrofoil underwater at various speed that can generate lift and describes how high the boat will theoretically be out of the water (Figure 5).

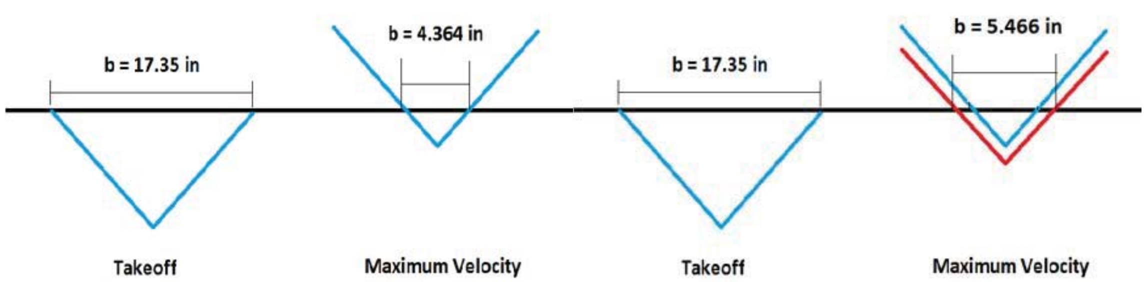


Figure 5: Visualization of calculated wetted span for hydrofoil system without autonomous control system weight (left) and with autonomous control (right).

3.4 DETAILED DESIGN AND MANUFACTURING PROCESS

Detailed working drawings for each part can be found in the Appendix A.2.

3.4.1 MOUNTING MECHANISM SUBASSEMBLY

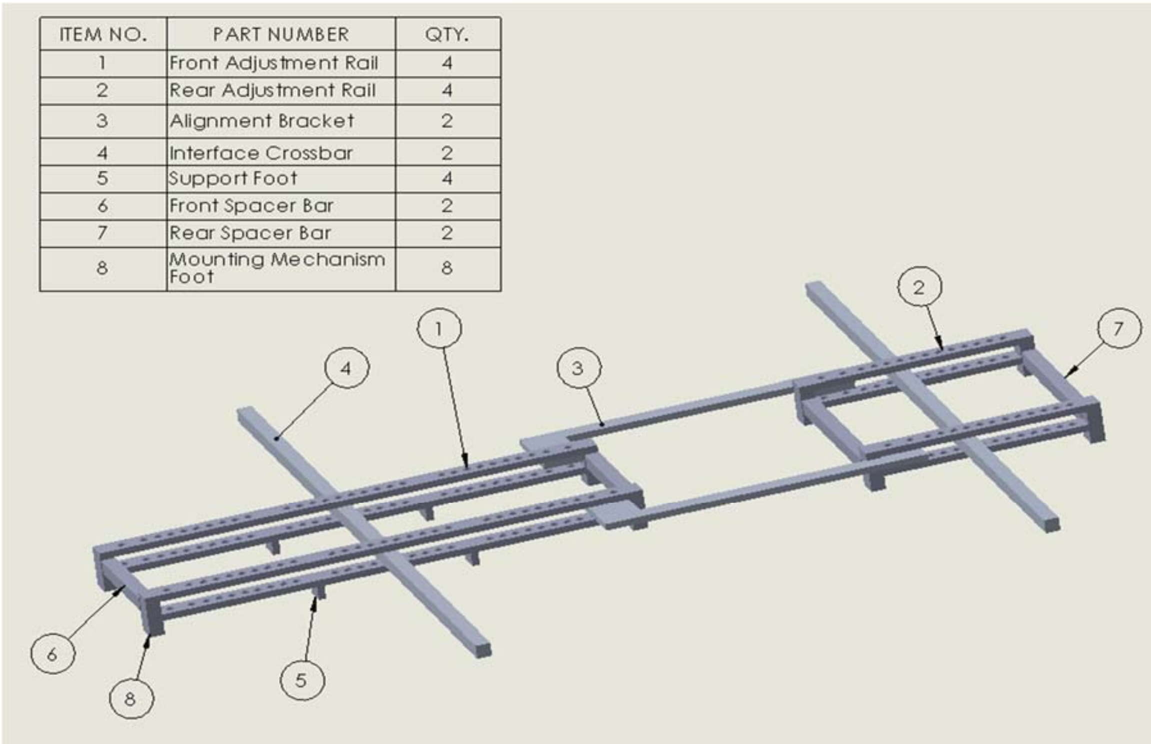


Figure 6: Mounting mechanism subassembly.

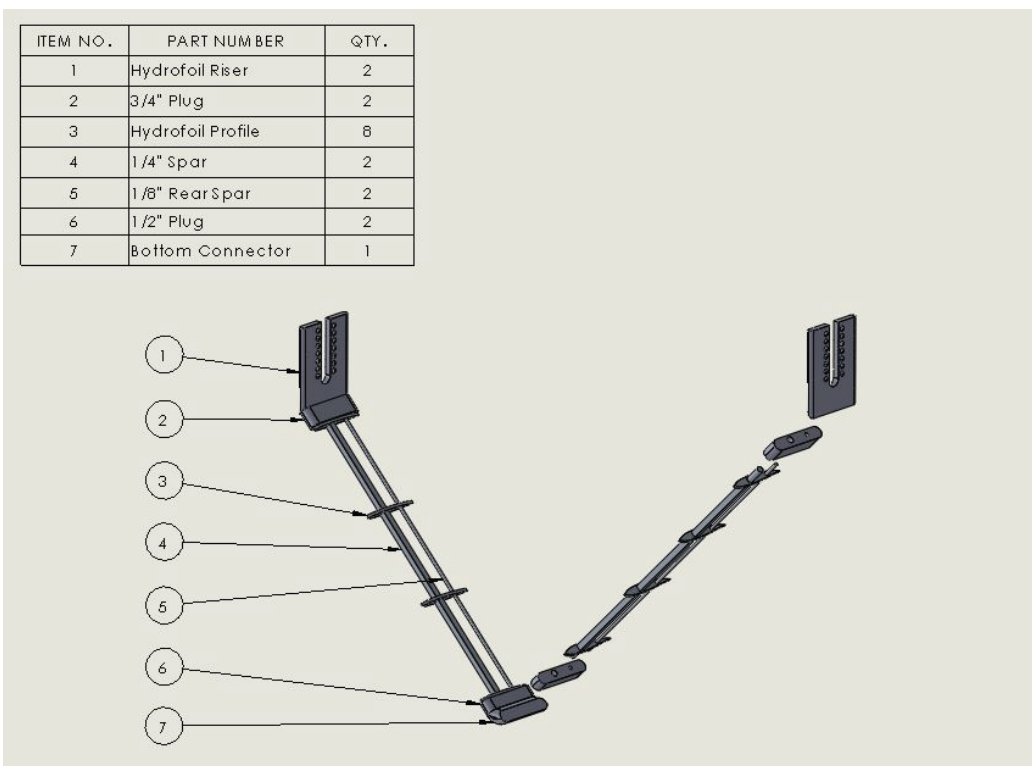
The mounting mechanism was designed to be lightweight, corrosion resistant, and strong. This was done by constructing all of the pieces out of 6061 aluminum.

The front and rear adjustment rails were constructed using ¾" wide by ¼" thick aluminum plate. The lengths were cut to size on the mill and then the holes were drilled precisely using the CNC mill (Figure 9, page 7). The alignment bracket was constructed using 2" wide by ¼" thick aluminum stock. The indented portion was rough cut using the band saw while the exact dimensions were cut using the mill. Holes were then drilled to match the holes in the alignment bracket. The interface crossbar was machined from ½" square aluminum stock. The length was cut to size and holes were drilled to match the holes in the alignment bracket using the mill. The mounting mechanism foot, the front space bar, and rear space bar were made on the mill from 1"x ¾" aluminum stock. All drilled holes were countersunk using the drill press and all burrs were removed from all cut surfaces using the grinding wheel. The mounting mechanism was then assembled (Figure 7).

Figure 7: Assembled mounting mechanism before welding took place.

The mounting mechanism feet were welded to the adjustment rails and the spacer bars using TIG welding. The welds were then filed down to make sure the alignment brackets would fit. The alignment brackets as well as the interface crossbars were then bolted in place using ¼"-20 bolts.

3.4.2 HYDROFOIL SUBASSEMBLY



ITEM NO.	PART NUMBER	QTY.
1	Hydrofoil Riser	2
2	3/4" Plug	2
3	Hydrofoil Profile	8
4	1/4" Spar	2
5	1/8" Rear Spar	2
6	1/2" Plug	2
7	Bottom Connector	1

Figure 8: Hydrofoil subassembly.

All the metal components of the hydrofoil subassembly were constructed using 6061 aluminum stock. The hydrofoil riser was rough cut using the marvel saw and then milled to size. The holes were drilled precisely using the CNC mill. To manufacture the inner notch, a special clamp was necessary to hold it in place (Figure 9).

Figure 9: Special clamping mechanism needed to cut center notch in hydrofoil risers

The ¾" and ½" plugs were rough cut using the marvel saw and exact dimensions cut using the mill. The hydrofoil profiles were cut out of ¼"x 2" stock material on the water jet by creating the profile in SolidWorks and transferring the DXF file.

The ¼" spar was turned down to a circle on both ends to fit into the plugs. Not shown in Figure 10 is the filler material placed between each aluminum hydrofoil profile. Initially these were going to be manufactured using foam. However, due to the small clearances between the spars and the edge of the profile, 3D printing was used. Using a STL file of the H105 profile, twelve spacers were made using a 3D printer (Figure 10).

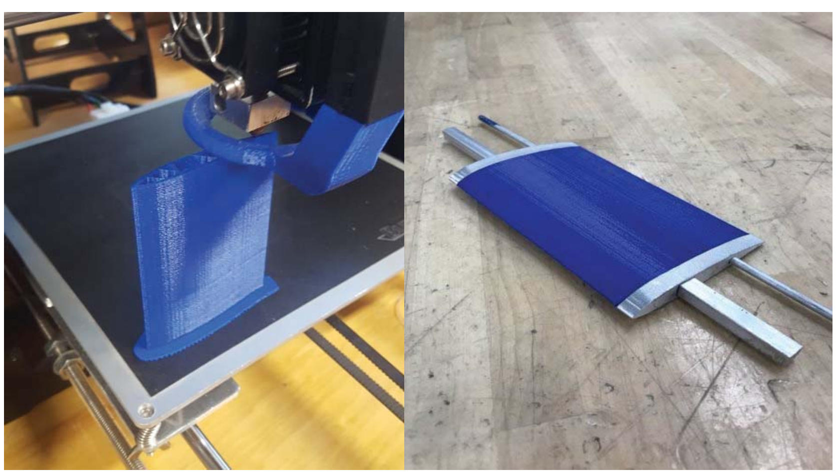


Figure 10: Printing the hydrofoil spacers and the final placement of a spacer on the hydrofoil skeleton.

The spars were slid through the profiles and spacers in an alternating pattern so that there was a single spacer between each profile so that each set of spars contained 4 profiles and 3 spacers (Figure 11).

Figure 11: Two spars with four profiles and three spacers each and arranged in a V-Shape configuration, pre-fiberglass layup.

Using Dr. Valeria La Saponara's composites lab, three layers of 0.73 oz plain weave fiberglass fabric were placed on the profiles using EZ Lam epoxy resin. The profiles were then placed in a vacuum bag and held under pressure for 24 hours. Figure 12 shows the hydrofoils inside the pressurized vacuum bags.

Figure 12: Hydrofoils during vacuum bagging process.

The plugs were secured to the hydrofoils with plug welds at the end. The plug welds were ground flat and two hydrofoils were welded to a bottom centerpiece. This resulted in a V-shape hydrofoil (Fig. 11). The bottoms of the hydrofoil risers were ground down to a 45-degree angle and welded to the top plug of each hydrofoil. Silicon was used to seal the hydrofoils where the fiberglass met with the metal plugs to prevent water from getting underneath the layers.

3.4.3 COMPLETE ASSEMBLY

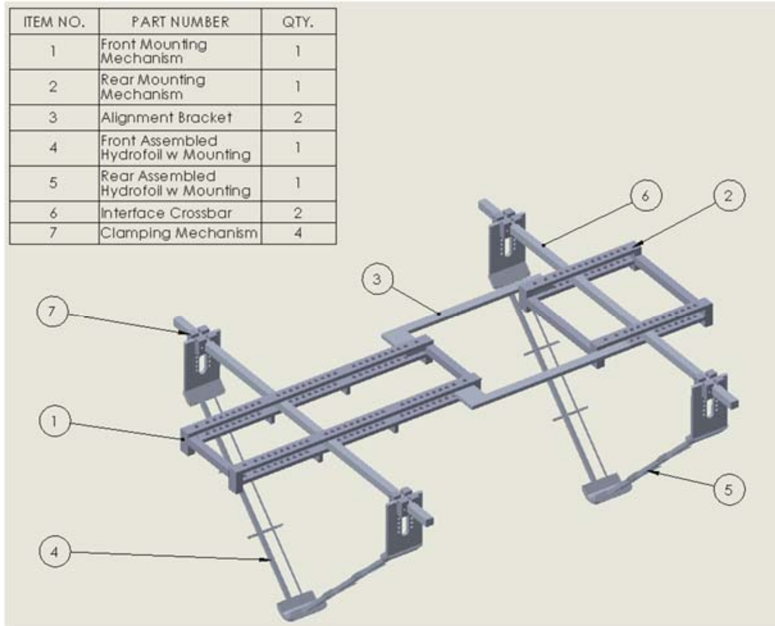


Figure 13: Complete mounting mechanism and hydrofoil assembly.

The hydrofoil subassembly will be connected to the mounting mechanism subassembly by a clamping mechanism attached to the interface crossbar. The clamping mechanism was machined out of 6061-aluminum. The clamping mechanism consists of 4 identical pieces that are used to secure the interface crossbar to the hydrofoil riser. Each piece is designed to have two bolts go across the interface crossbar and one bolt through the hydrofoil riser. These bolts are then tightened to an identical part directly across from it and tightened to secure the pieces together. This clamp can be seen in Figure 14.

Figure 14: Clamping mechanism, which attaches risers and mounting mechanism's crossbar.

3.4.4 HYDRO-KINETIC TURBINE SIMULATION DEVICE

To meet the requirement of a removable attachment to be able to simulate the hydro-kinetic turbine, a 3D printed component was design to fit over the keel using zip-ties connecting to L-brackets and a holding ring (Figure 15). The front plate was designed to cup the front of the keel so that the frontal area would be perpendicular to the flow to approximate the additional drag of a hydro-kinetic turbine.

Figure 15: 3D printed mockup of drag plate for drag-reduction testing.

3.4.5 TOTAL COST

The total cost of materials and hardware was $546.75. The complete bill of materials can be found in Figure 41 in the Appendix.

4 ANALYSES

4.1 STATIC LOAD ANALYSIS

Our structural analysis consists of simulated testing with the built-in SolidWorks FEA suite. Initial static load testing was performed to assure that each foil and the frame could withstand half of the weight of the entire boat and frame assembly (15 lb.) with an extra factor of drag force (5 lb.) included based on our calculated drag loads. Through this work, we found a worst-case scenario factor-of-safety of 9.27 which lead us to believe in the design and commit to further testing.

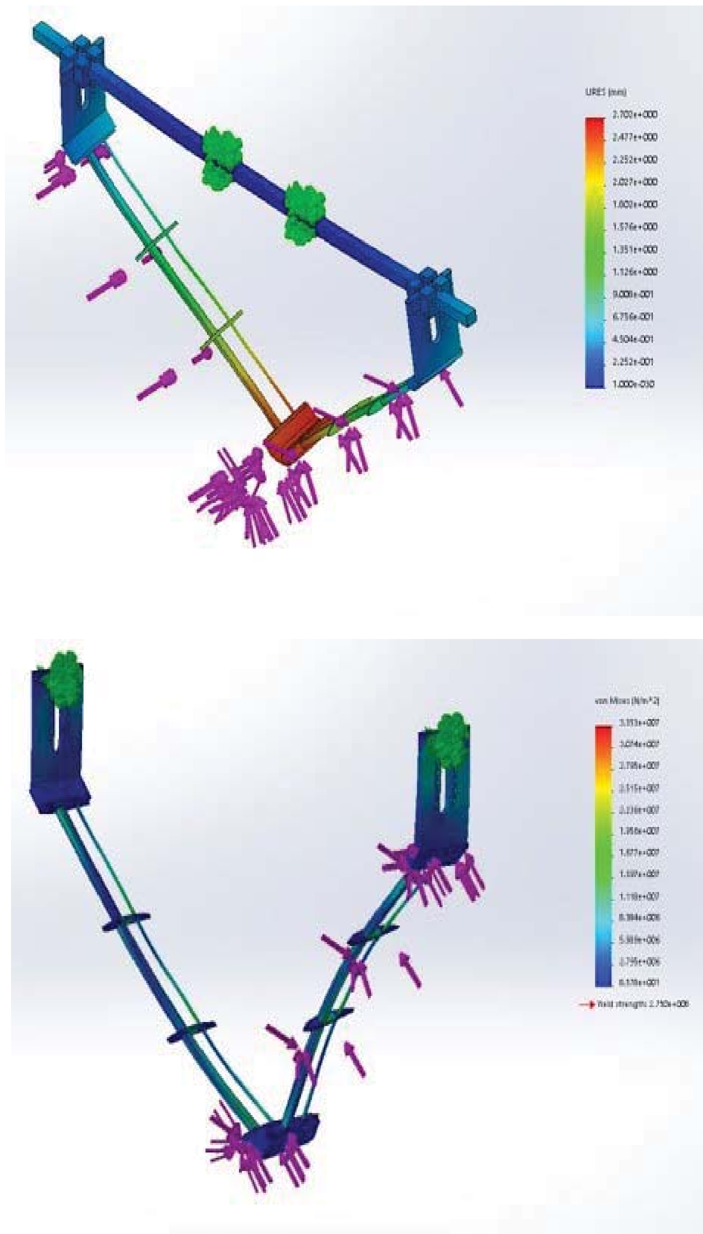


Figure 16: Static load testing of hydrofoil skeletons and crossbars.

4.2 DYNAMIC/VIBRATIONAL LOAD TESTING

Vibrational testing was done at similar load conditions. The structure had three rigid-body modes and three nearly rigid-body modes which most likely can be attributed to the six natural degrees-of-freedom of the system (Fig. 17). The most interesting modal frequencies were found to exist at $1.79(10^{-2})$ and $2.45(10^{-2})$ Hz, which correspond to a vibrational period of 55.832 and 40.863 seconds, respectively. These two modes lie well outside the peak-power of the wave power spectrum (Fig. 18) but were nearest to the frequency with maximal power and so were used to simulate a worst-case or nearly resonant state. These two frequencies were used as testing input with the loads provided by the static testing at a dynamic load factor of 2.0 (~30 lb.) finding minimal material displacement ($3.75(10^{-11})$ mm) and nearly zero stress on the frame at these load conditions (Figures 19 and 20 on the next two pages).

List Modes

Study name:Dynamic 1

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	0	0	1e+032
2	0	0	1e+032
3	0	0	1e+032
4	0.0038613	0.00061455	1627.2
5	0.0043241	0.0006882	1453.1
6	0.0051395	0.00081798	1222.5
7	0.11254	0.017911	55.832
8	0.15376	0.024472	40.863
9	162.09	25.798	0.038763
10	189.34	30.134	0.033185
11	334.31	53.207	0.018794
12	513.98	81.803	0.012225
13	542.44	86.333	0.011583
14	643.02	102.34	0.0097714
15	678.25	107.95	0.0092638

Close Save Help

Figure 17: Vibrational modes of the full assembly. Notice there are six nearly rigid-body modes, one for each degree of freedom. The modes which match most closely the expected vibrational loading of ocean waves are at mode numbers 7 and 8.

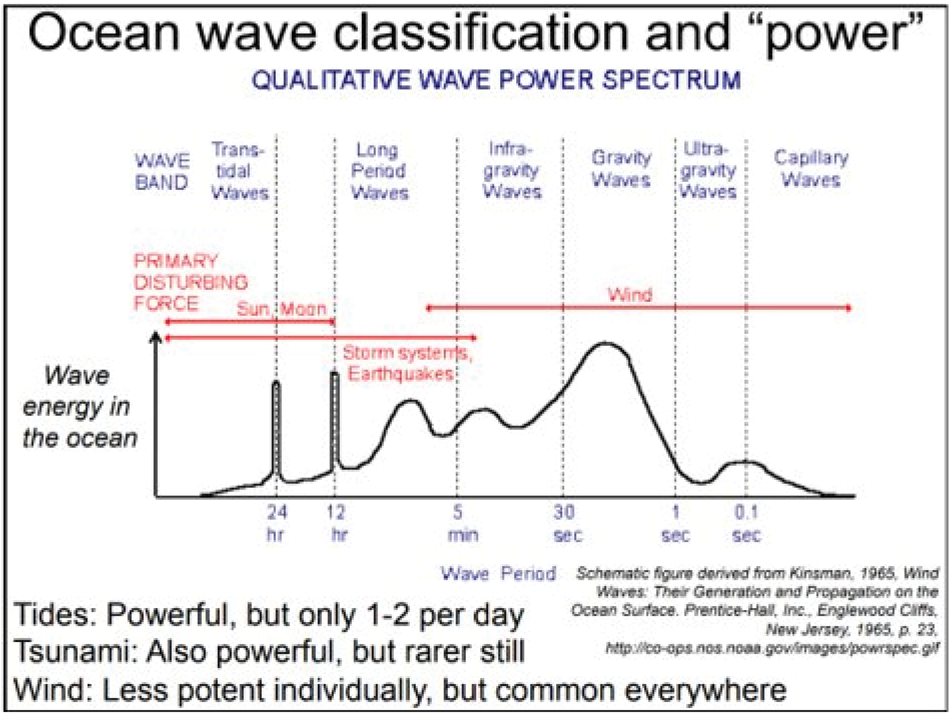


Figure 18: Power spectrum of ocean waves. This was used to quantify the most susceptible vibrational modes of the system for further testing.

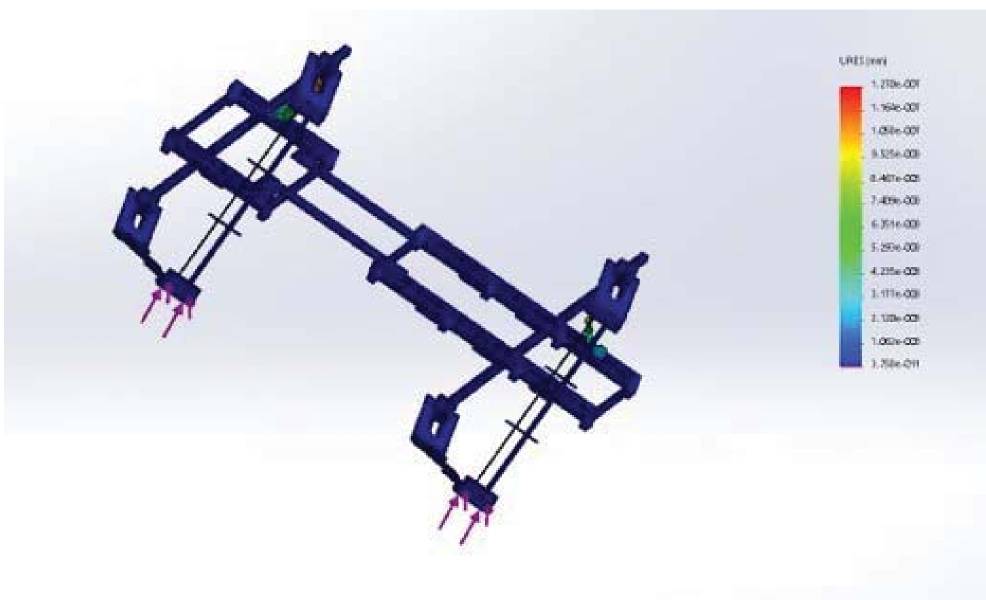


Figure 19: FEA analysis which shows displacement due to vibration.

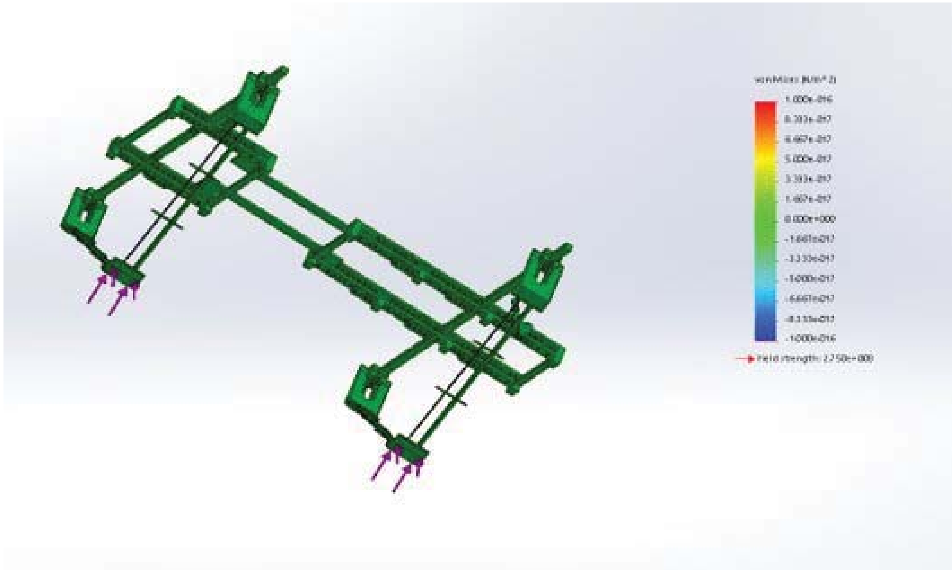


Figure 20: FEA analysis which shows stress due to vibration.

4.3 FATIGUE/LIFE-EXPECTANCY ANALYSIS

Finally, a one-million cycle, fully-reversed fatigue analysis was conducted under two conditions, maximal expected loading of twice the weight of the system (~30 lb.) and then again at three-times the maximal expected conditions (~90 lbs.). Under normal wave conditions, the expected maximal wave-to-ship power delivery frequency period was found to around 20 seconds giving nearly 5600 hours operating life at 1,000,000 cycles. Assuming resonance to occur at a vibrational period of around 50 seconds, the expected operating life is 14,000 hours. Based on a 12-hour working day, this would provide a minimum of 1.27 years of operation under the worst-case scenario.

Under the maximal expected loading-condition, the "damage percentage" (a measure of the amount of energy absorbed by the system) of the structure was found to be only about 9%. Under the worst-case scenario of three-times loading, the "damage percentage" was increased slightly more six times to about 58.3% (Figure 21, on following page).

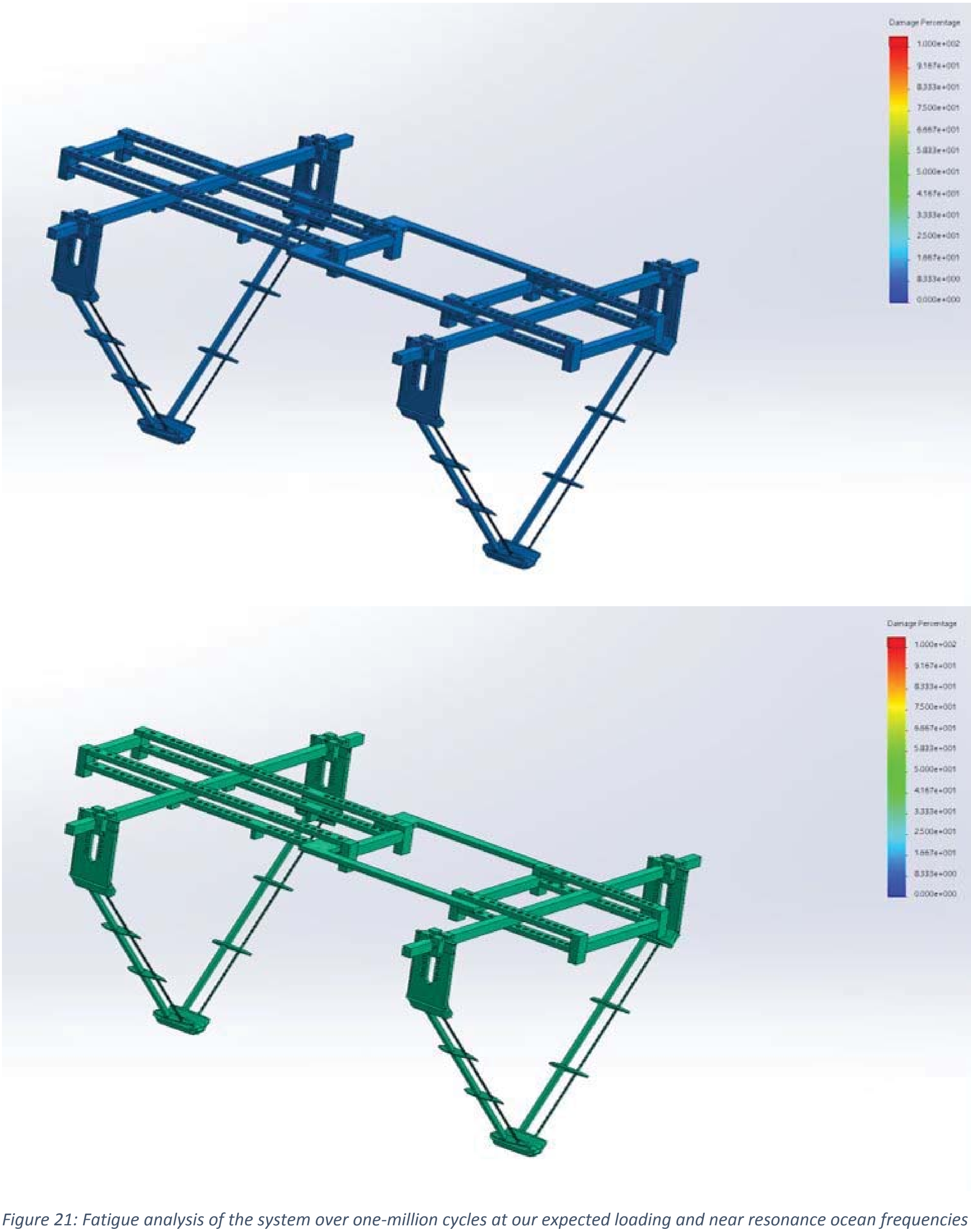


Figure 21: Fatigue analysis of the system over one-million cycles at our expected loading and near resonance ocean frequencies (top) give the design about a 9% spent life, while at three-times expected loading under the same conditions, the design still was only damaged around 58%.

5 MATERIAL STANDARDS

According to the American Boat & Yacht Council, only aluminum alloys from the following table should be used in the construction of submerged parts:

9. Keel			same as hull
10. Keel/extruded	• 6061-T4, T6 • 6062-T4, T6	• 6061-T4 • 6063-T6	
11. Keel/formed sheet	• 5082-H34 • 5086-H116, H117 • 5154-H34	• 5052-H34 • 5086-H116, H117	
12. Frames	same as keel	same as keel	• 5086-H116, H117 • 6061-T6
13. Longitudinals			same as hull
14. Splash rails	same as keel	same as keel	

Figure 22: The standard material used for submerged parts is 6061 aluminum (American Yacht and Boat Council, 2011).

The standard materials for frames are 5086-H116, H117 and 6061-T6 aluminum. The latter material was chosen due to the following factors:

- Greater yield strength than 5086
  - 35,000 psi (6061) vs 17,000 psi (5086)
- Ease of manufacturing
- Availability
- Comparable cost to 5086 alloys

6 TESTING

The fully assembled boat was taken out to Lake Chabot in Vallejo, CA to test the hydrofoil system. During testing, wind conditions were very sporadic which limited the ability to sail the boat. According to data collected using an anemometer, the maximum speed reached by the boat was 2.8 mph which was well below the designed take-off speed of 6.7 mph.

To compensate for the lack of wind, the boat was then towed by a small RC speed boat. The boat successfully semi-foiled although was unable to be pulled fast enough to full-foil (Fig. 23).

Figure 23: Model LASER sailboat semi-foiling while being towed by RC speed boat.

The boat was also tested at Stonegate Lake in Davis, CA. The winds were more consistent during this test day. While trying to sail the boat in full foil and semi-foil mode, the boat would not follow a straight path with the wind. Even with an experienced sailor controlling the boat, as soon as the boat would begin to pick up some speed, the rudder appeared to bend causing the boat to turn into the direction of the wind.

7 STRENGTHS AND WEAKNESSES

The hydrofoil system was lightweight, strong, and helped the sailboat maintain stability. During testing, when gusts of wind would hit the sail, the boat would begin to tip. With the hydrofoil system in place, the boat would immediately correct and right itself. The system also crashed into walls, a kayak, and docks without breaking. The V-shape design of the hydrofoil eliminated the need for an adjustable angle of attack which reduced the complexity of the design and the cost.

With the inability of the sailboat to reach the required speed to achieve full foil (roughly 3 m/s), it is difficult to say whether the design worked or not. One area that could have been improved was the strap system used to hold the boat and mounting mechanism together. The strap system used consisted of a simple backpack clip and synch style. Since the clips were small and cheap, they had a difficult time being synched tightly.

The greatest issue faced was that the size of the RC sailboat limits its ability to achieve high speeds. Due to the way that the RC works on the sailboat, a single string controls the sail moving in and out. If the wind isn't hitting the sail just right as the string is letting the sail out, the sail would just flap around. This makes it difficult to sail the boat. When the boat is sailing with the wind, we observed the rudder bend which caused the boat to change directions.

8 FUTURE CHANGES

8.1 Current Design

When testing, the nylon straps proved difficult to tighten adequately. Instead of using the cheap backpack clip straps, installing ratcheting straps would better ensure that the entire hydrofoil system is firmly attached. Due to the impact of weight on the performance of the system, a lower factor of safety should be used to minimize this impact from the mounting mechanism itself. A substantial decrease in weight could be achieved by using square tubing instead of square stock material

To successfully full-foil, iterations on the rear foil configuration is necessary. In the current design, the front and rear foiling systems weigh approximately the same therefore doubling the total weight when transitioning from semi-foiling to full-foiling mode. Cutting weight from rear foil by either downsizing the V-foil while maintaining the lift or using a T-foil would limit the impact on the take-off speeds necessary.

8.2 Future Testing

For preliminary testing, a hydraulic flume or tow tank would allow measurements of the actual take-off velocities and ride heights of the design during each of the modes with and without the simulation of the hydro-kinetic turbine. This would provide more accurate and consistent data collection to make comparisons between the performance of the different hydrofoil configurations. In addition, force sensors could be applied to measure actual lift and drag forces to verify calculations. For open water testing, a motorized vehicle with variable speeds should be used to tow the boat to get up to the adequate speeds for foiling.

9 CONCLUSIONS

Overall, the end-product met nearly all of the specifications. Further testing can confirm whether the boat successfully semi and full foils in the desired wind conditions. No speed data was recorded during the successful semi-foil test runs; therefore, no conclusions can be made about the actual take-off velocities at this point. The entire system is easily removable from the RC Laser boat by unclipping the two straps. The rear foil system can be removed by unbolting the alignment brackets to switch from full-foil to semi-foil. The addition of the autonomous control was taken into consideration during the design phase. No tests were run with the hydro-kinetic turbine simulation device due to the inability to sail the boat under optimum wind conditions. The total cost of the design was $546.75 which fell well below the budget of $1000.

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APPENDIX

A.1 ADDITIONAL ANALYSIS FIGURES

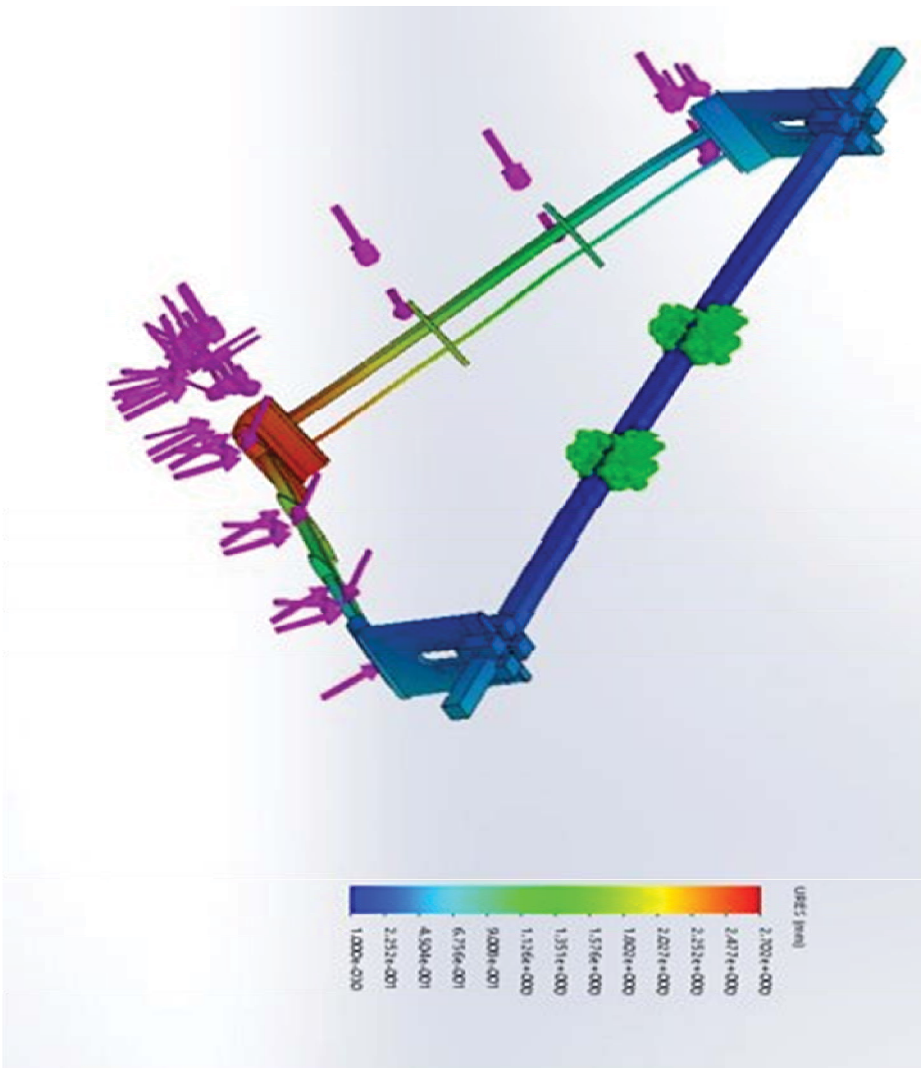

Figure 24: At a 15 lb. lift force with a constant 5lb distributed drag force, the cross-bar deflection was simulated as merely 2.7mm.

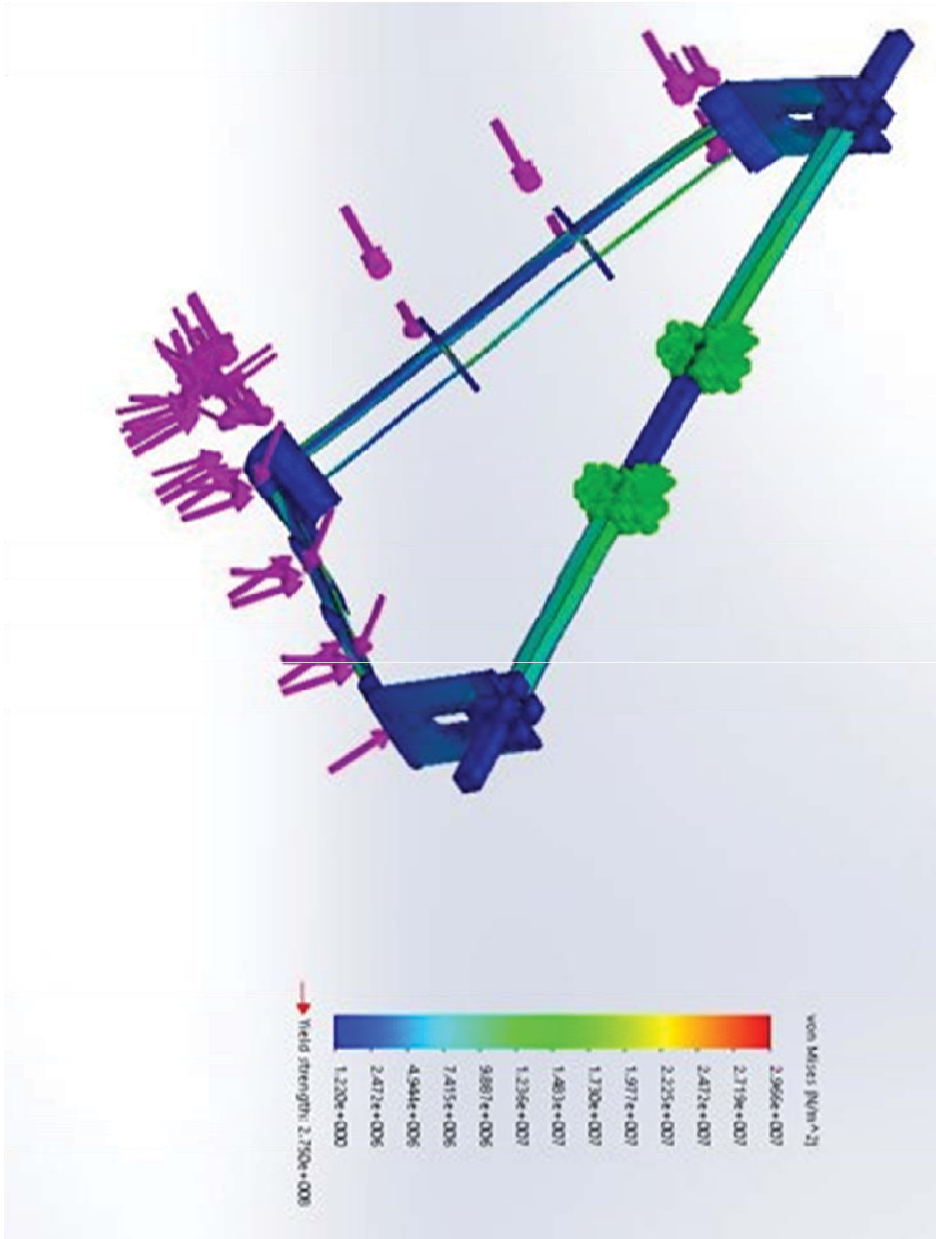

Figure 25: At the same loads as in Fig. 24, the factor-of-safety was found to be 9.27.

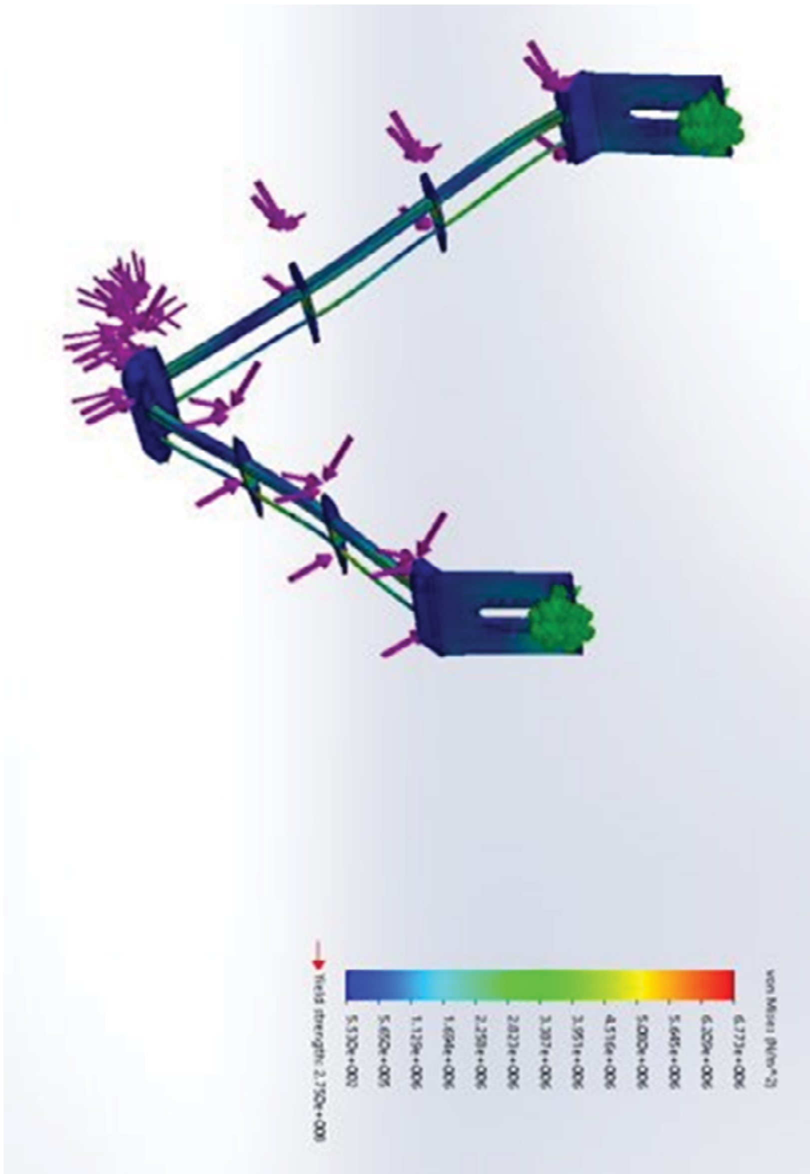

Figure 26: Under the same load conditions as Figs. 24-25, the factor-of-safety on the hydrofoil skeleton was found to be 10.5.

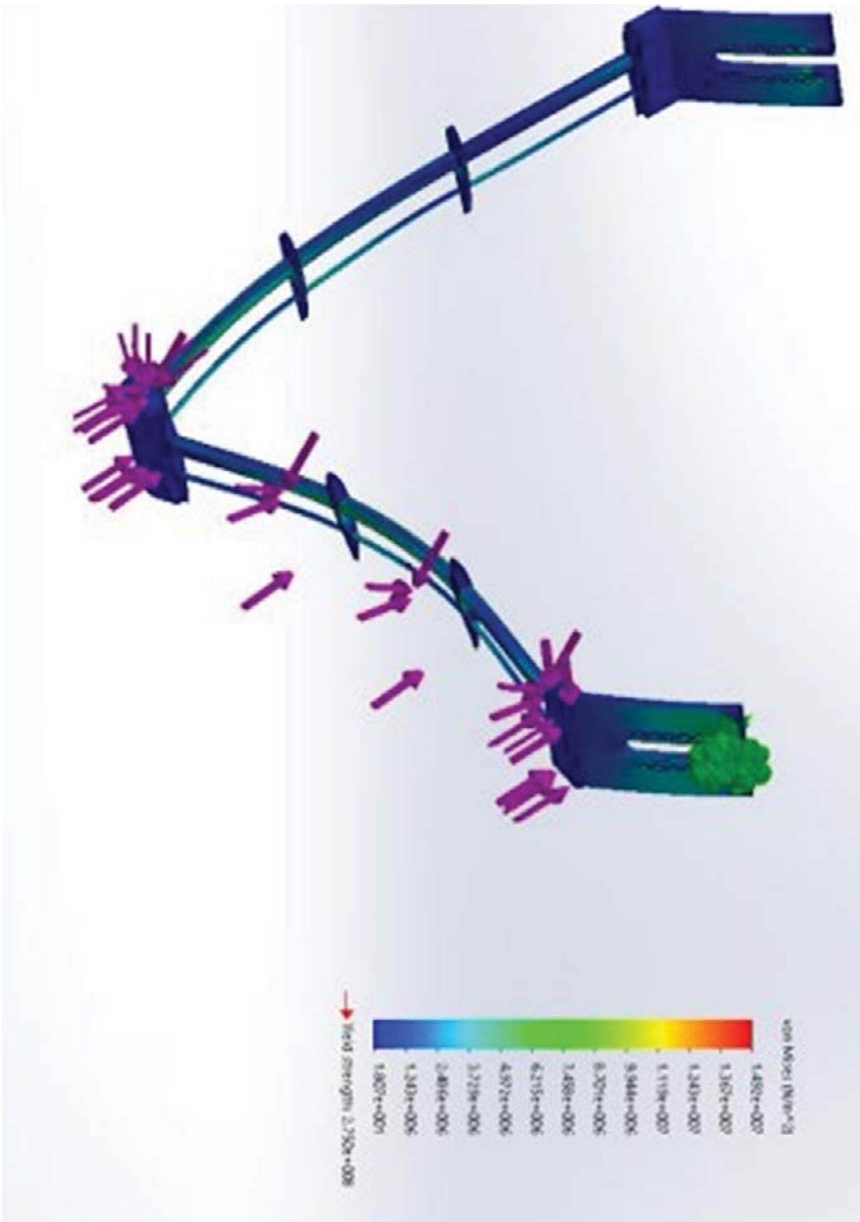

Figure 27: Under the same conditions as the previous figures, but with a 45-degree lean, the hydrofoil skeleton was simulated as having a FOS of 18.4.

A.2 WORKING DRAWINGS

(ALL DIMENSIONS IN INCHES)

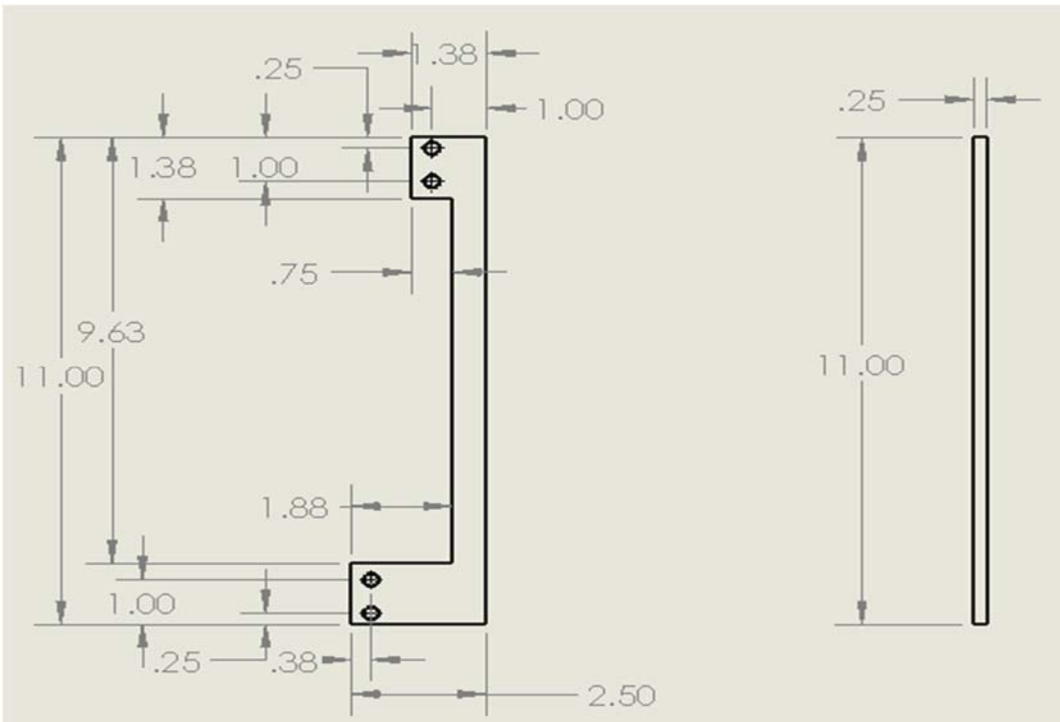

Figure 28: Alignment Bracket.

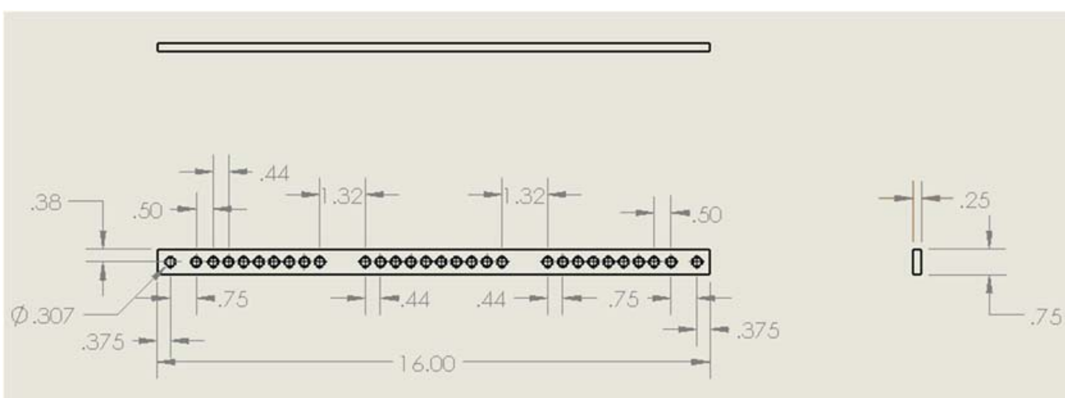

Figure 29: Front Adjustment Rail.

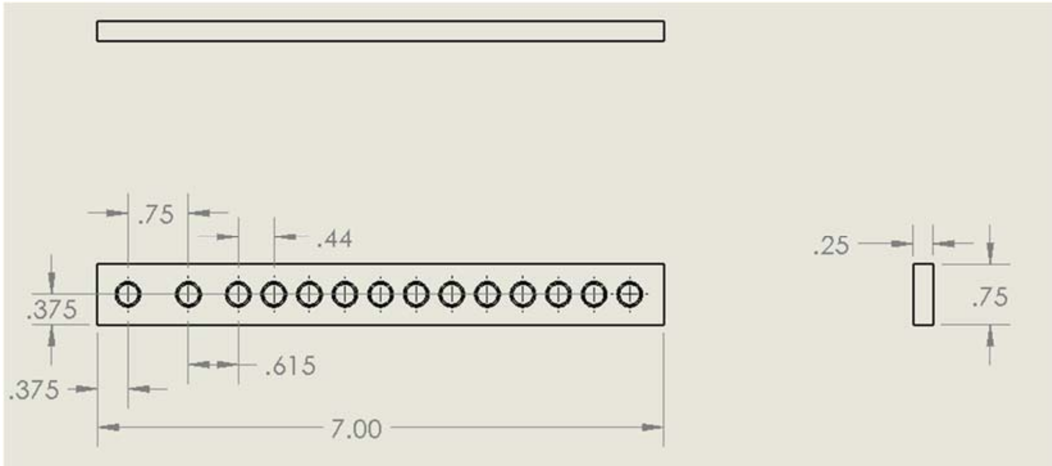

Figure 30: Rear Adjustment Rail.

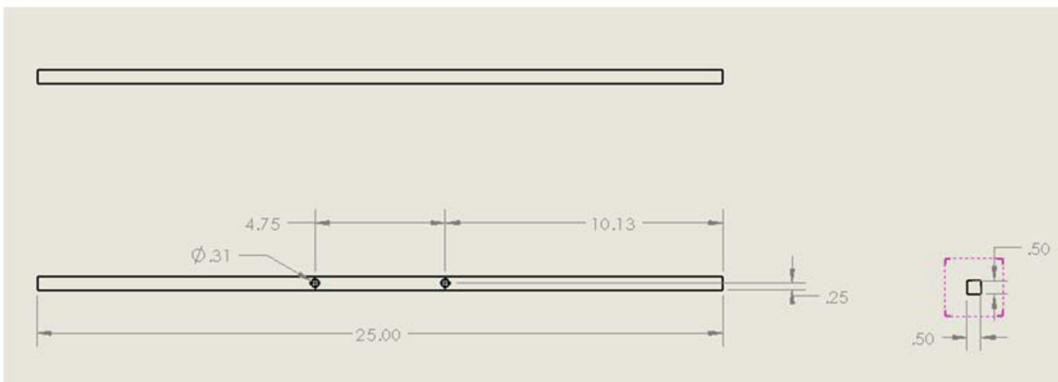

Figure 31: Front Interface Crossbar.

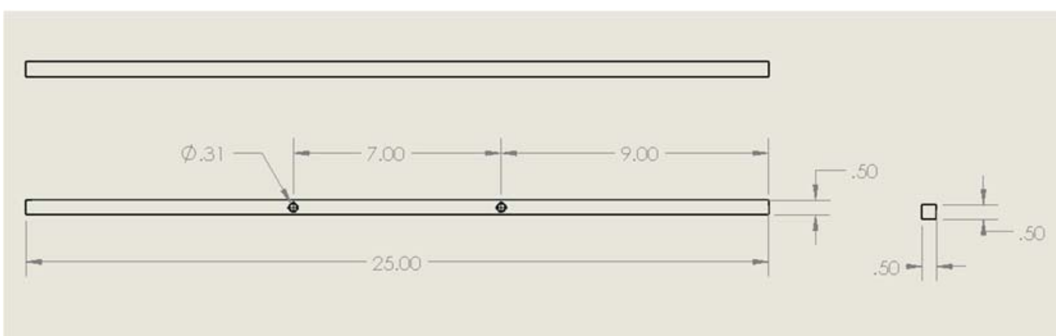

Figure 32: Rear Interface Crossbar.

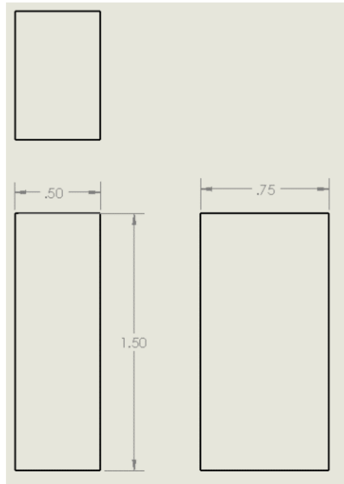

Figure 33: Mounting Mechanism Foot.

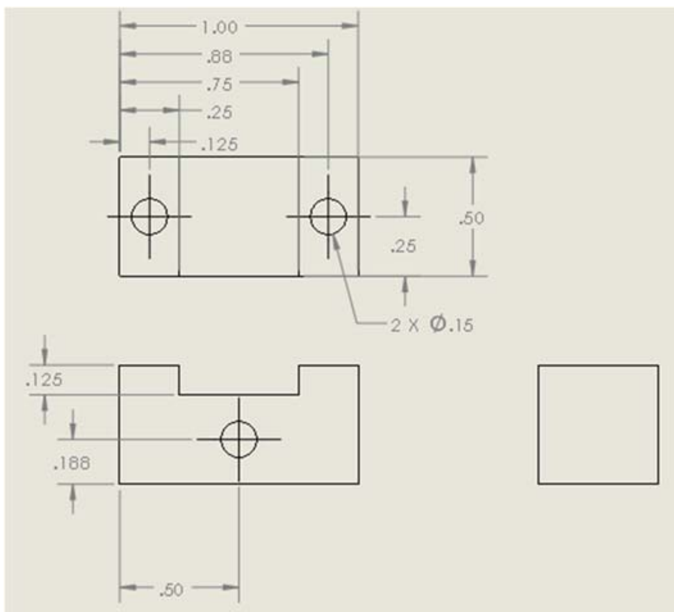

Figure 34: Clamping Mechanism (x4 per clamp).

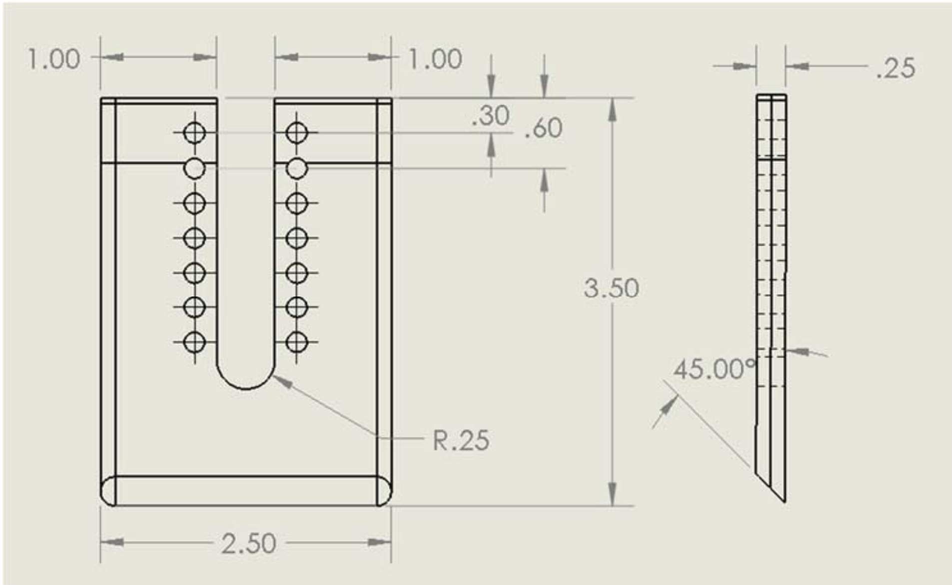

Figure 35: Hydrofoil Riser.

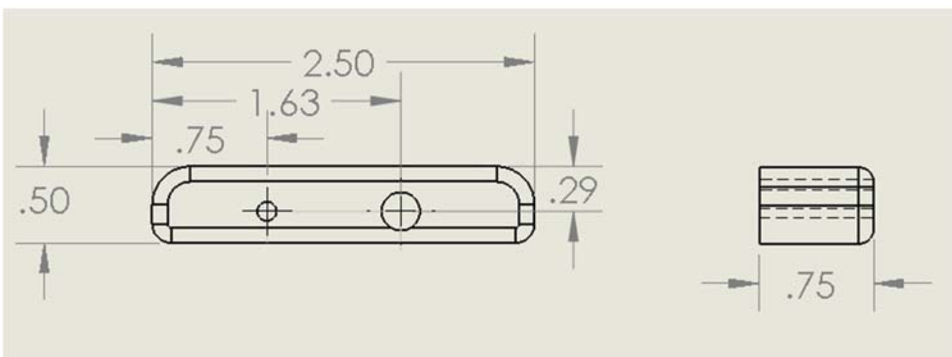

Figure 36: 3/4" Plug.

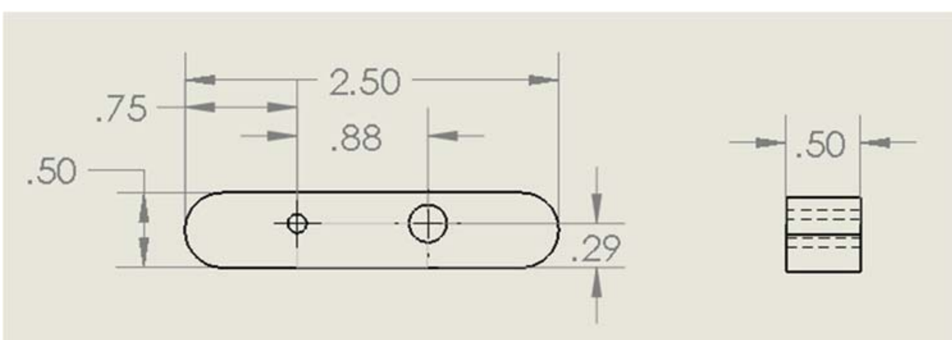

Figure 37: 1/2" Plug.

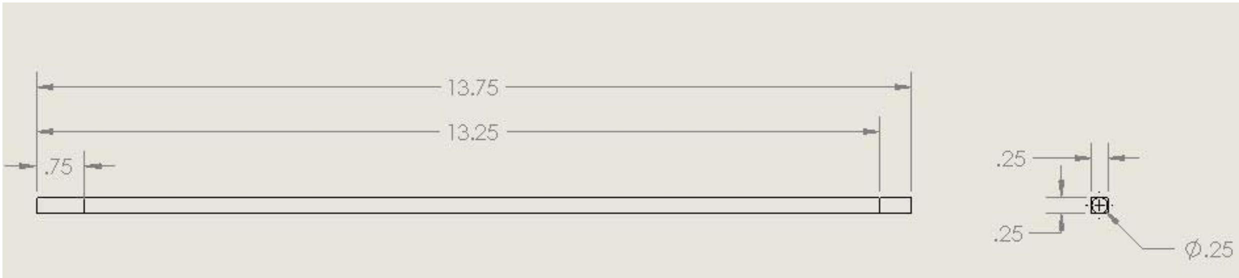

Figure 38: 1/4" Spar.

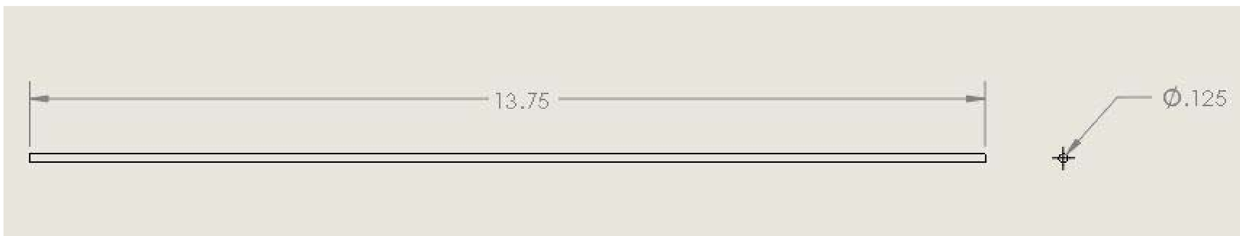

Figure 39: 1/8" Rear Spar.

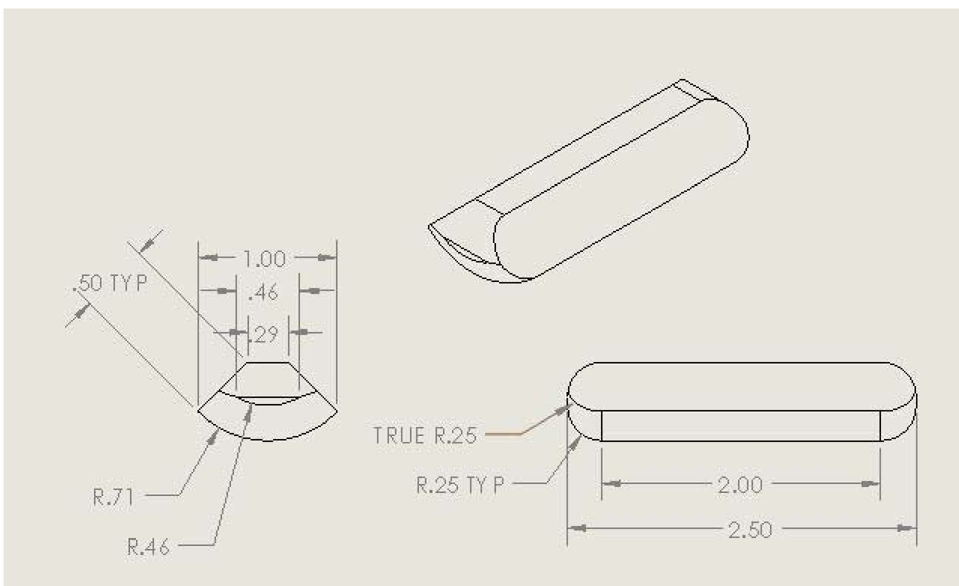

Figure 40: Bottom Connector.

Project Component	Product Description	Size	Quant.	Total Price
Mount. Mech. Reinforcement	3/4x1/4 6061 Rectangular Stock	6 ft	2	$17.86
Hydrofoil Attachment Bars	1/2" 6061 SQ Stock	6 ft	2	$22.72
Hydrofoil Profiles/Mount. Mech.	2" x 48" Bar Stock (1/4" Thick)	1 unit	1	$28.76
Hydrofoil Profiles	6061 Aluminum, 1/8" Thick x 1" Wide	2 ft	1	$2.56
Struts	6061 Aluminum 6"x12" Bar Stock (1/4" thick)	1 ft	2	$26.74
Hydrofoil Skeleton	6061 Aluminum 1/4"x1/4" Bar Stock	3 ft	2	$6.58
Hydrofoil Skeleton	6061 Aluminum 1/8" Round Stock	3 ft	2	$4.18
Mounting Linkages	6061 Aluminum 2"x3" Bar Stock	0.5 ft	1	$28.88
Mouning Arm	6061 Aluminum 3/4"x1" Bar Stock	2 ft	1	$12.51
Mounting Arm Attachment	1/4"-20 Bolt 1-1/2" Length	50/pack	1	$7.91
Mounting Arm Attachment	1/4"-20 Bolt 1-3/8" Length	50/pack	1	$10.38
Mounting Arm Attachment	6-32 Screw 1-1/2" length	25/pack	1	$9.21
Mounting Arm Attachment	1/4" Washer	100/pack	1	$8.25
Mounting Arm Attachment	1/4"-20 Hex Nut	50/pack	1	$2.27
Mounting Arm Attachment	6-32 Hex Nut	100/pack	1	$3.40
Hydrofoil Layup	Supply Kit for Pro Plus Vacuum System	1 kit	1	$114.40
Hydrofoil Layup	0.73 oz. Plain Weave Fiberglass Fabric 38" 2 Yds.	1 unit	1	$11.50
Hydrofoil Layup	8 oz. Polymixing Cup	1 unit	1	$0.65
Hydrofoil Layup	Plastic Squeegy	1 unit	1	$5.73
Hydrofoil Layup	Reusable Mixing Sticks	1 unit	1	$3.71
Hydrofoil Layup	1" Disposable Brushes	1 unit	1	$2.95
Hydrofoil Layup	Carbon Fiber Woven Tape (2"x3yards)	1 unit	1	$31.45
Hydrofoil Layup	EZ-Lam Epoxy resin (30 minute) 48 oz. kit	1 unit	1	$50.00
Hydrofoil Layup	3" Epoxy Roller kit	1 unit	1	$10.00
Finish	12-oz Lacquer clear gloss	1 unit	1	$5.07
Finish	Spray Paint (gold)	1 unit	1	$4.30
Finish	Spray Paint (blue)	1 unit	1	$4.30
Finish	Silicon Caulk	1 unit	1	$6.16
Finish	Spool of PLA	1 unit	1	$26.03
Shipping Costs				$46.75
Sales Tax				$31.54
Total				**$546.75**

Figure 41: Bill of materials for entire project cost.

A.3 Hydrofoil Dimensioning Code

File:HydrofoilAnalysis_WettedAreaAnalysis_Complex.EES64 6/6/2018 5:41:36 PM Page 1
EES Ver. 10.295: #4315: For use only by students and faculty, Mechanical & Aero Engr., Univ. California - Davis

Water Properties

$\rho = 998.23$ [kg/m³] *density of water*

$\mu = 0.001002$ [Pa·s] *viscosity of water*

Hydrofoil Properties

$th_r = 0.125 \cdot ch_r$ *thickness for H105*

$th_f = 0.125 \cdot ch_f$

$L_f = \dfrac{b_f}{2^{0.5}}$ *length of hydrofoil*

$L_r = \dfrac{b_r}{2^{0.5}}$

$AR_f = 7$ *Aspect Ratio front*

$AR_f = \dfrac{b_f}{ch_f}$

$AR_r = 7$ *Aspect Ratio rear*

$AR_r = \dfrac{b_r}{ch_r}$

Boat Properties

$x_{rear} = 11 \cdot 0.0254$ [m] *distance from CG location*

$x_{front} = 11 \cdot 0.0254$ [m]

$g = 9.8$ [m/s²] *gravity acceleration*

$m_{boat} = 7.75 \cdot 0.454$ [kg] *mass of boat and keel*

$m_{mount} = 8 \cdot 0.454$ [kg] *mass of mounting mechanism*

$W = (m_{boat} + m_{mount}) \cdot g$ *weight of boat*

$V_{max} = 5$ [m/s] *maximum speed*

$V_{to} = \dfrac{V_{max}}{2}$ *takeoff speed*

Coefficients

$C_L = 0.4$ *coefficient of lift*

$C_D = 0.01 + \dfrac{C_L^{\ 2}}{3.14 \cdot 0.95 \cdot AR_r}$ *coefficient of drag*

Force Equilibrium

$W = Lift_{rear} + Lift_{front}$ *Force balance*

$Lift_{rear} \cdot x_{rear} = Lift_{front} \cdot x_{front}$ *Moment balance*

Calculations at Take Off

$q_{to} = 0.5 \cdot \rho \cdot V_{to} \cdot V_{to}$

$Lift_{rear} = q_{to} \cdot S_{rear} \cdot C_L$

$Lift_{front} = q_{to} \cdot S_{front} \cdot C_L$

$S_{rear} = ch_r \cdot b_r$ *wetted surface area at takeoff*

$S_{front} = ch_f \cdot b_f$

Calculations at Maximum Height

$q_{foil} = 0.5 \cdot \rho \cdot V_{max} \cdot V_{max}$

$Lift_{rear} = q_{foil} \cdot S_{wetrear} \cdot C_L$

$Lift_{front} = q_{foil} \cdot S_{wetfront} \cdot C_L$

$S_{wetrear} = ch_r \cdot b_{rmin}$ *wetted surface area at maximum height*

$S_{wetfront} = ch_f \cdot b_{fmin}$

print in inches

$length_r = 39.3701 \cdot L_r$

$length_f = 39.3701 \cdot L_f$

$chord_r = 39.3701 \cdot ch_r$

$chord_f = 39.3701 \cdot ch_f$

$span_f = b_f \cdot 39.3701$

$span_r = b_r \cdot 39.3701$

$span_{fmin} = 39.3701 \cdot b_{fmin}$

$span_{rmin} = 39.3701 \cdot b_{rmin}$

$thick_r = 39.3701 \cdot th_r$

$thick_f = 39.3701 \cdot th_f$

Drag calculations

$fdrag_{to} = C_D \cdot q_{to} \cdot S_{front}$

$$rdrag_{to} = C_D \cdot q_{to} \cdot S_{rear}$$

$$drag_{to} = fdrag_{to} + rdrag_{to}$$

$$fdrag_{max} = C_D \cdot q_{foil} \cdot S_{wetfront}$$

$$rdrag_{max} = C_D \cdot q_{foil} \cdot S_{wetrear}$$

$$drag_{max} = fdrag_{max} + rdrag_{max}$$

$$wind_{drag} = 0.613 \cdot \frac{4580}{100^2} \cdot V_{max}^2 \cdot 1.4$$

SOLUTION

Unit Settings: SI C Pa J mass deg

$AR_f = 7$
$b_f = 0.4433$
$b_r = 0.4433$
$chord_f = 2.494$
$ch_f = 0.06334$
$C_D = 0.01766$
$drag_{max} = 3.094$
$fdrag_{max} = 1.547$
$g = 9.8$ [m/s^2]
$length_r = 12.34$
$Lift_{rear} = 35.04$
$L_f = 0.3135$
$m_{boat} = 3.519$
$q_{foil} = 12478$
$rdrag_{max} = 1.547$
$\rho = 998.2$ [kg/m^3]
$span_{fmin} = 4.364$
$span_{rmin} = 4.364$
$S_{rear} = 0.02808$
$S_{wetrear} = 0.00702$
$thick_f = 0.3117$
$th_f = 0.007917$
$V_{to} = 2.5$
$wind_{drag} = 9.826$
$x_{rear} = 0.2794$

$AR_r = 7$
$b_{fmin} = 0.1108$
$b_{rmin} = 0.1108$
$chord_r = 2.494$
$ch_r = 0.06334$
$C_L = 0.4$
$drag_{to} = 3.094$
$fdrag_{to} = 1.547$
$length_f = 12.34$
$Lift_{front} = 35.04$
$L_r = 0.3135$
$\mu = 0.001002$ [Pa·s]
$m_{mount} = 3.632$
$q_{to} = 3119$
$rdrag_{to} = 1.547$
$span_f = 17.45$
$span_r = 17.45$
$S_{front} = 0.02808$
$S_{wetfront} = 0.00702$
$thick_r = 0.3117$
$th_r = 0.007917$
$V_{max} = 5$ [m/s]
$W = 70.07$
$x_{front} = 0.2794$

9 potential unit problems were detected.

m