On the design and manufacturing choices to obtain a stable canard hydrofoil system for a low speed solar boat

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ABSTRACT

The purpose of this paper is to give an overview of the design decisions made in order to obtain a stable hydrofoil system for a solar powered boat. Cedarville University has won the Solar Splash Collegiate World Championship of Solar Boating nine times. Furthermore, Cedarville University was the top university in the Top Class of the 2012 DONG Energy Solar Challenge in the Netherlands (renamed DSC, Dutch Solar Challenge). In addition to this year's Solar Splash, Cedarville University will be participating in the DSC with an overall objective to achieve first place. The DSC is a bi-annual week-long race known also as the World Cup for Solar Powered Boats that is open to both universities and companies. This race consists of long endurance portions and sprint portions. Based upon previous competition winners, it was determined that hydrofoils are necessary to complete this objective. Hydrofoils provide a unique advantage by lifting the hull of the boat out of the water, and decreasing the drag above the takeoff speed. The following paper will describe the design of elliptical hydrofoils with the key design parameters being strength, drag, lift, and stability of the system. The creation and use of two complex Matlab codes for the design of hydrofoils will be touched upon. The front assembly and articulation design to manage height will be discussed. The combination of the lower gear unit of the drive train and the rear hydrofoil articulation in the same pod will be explored. Finally, the manufacturing methods of the strut and hydrofoils using a CNC machine will be explained.

INTRODUCTION

In order to meet the objective of winning the Dutch Solar Challenge, specifications were dictated in the power budget. This budget provides the most efficient thrust from the propellers at the average velocity necessary to win the race. The primary goal for the hydrofoil team was to have the drag be less than or equal to the thrust of 125 N at 36 km/hr while creating lift equaling the weight of the boat of 2446 N.

General hydrofoil profile and planform area were determined through the use of MIT programs Xfoil and AVL. Xfoil determines the coefficient of parasitic drag (C_{do}) based upon a viscous modelling of a chosen profile. This allowed for an initial profile choice of the MH115. Athena Vortex Lattice (AVL) is an inviscid solver used to evaluate the coefficient of lift and coefficient of induced drag (C_{di}) based upon the planform area and profile.

In addition to hydrofoil analysis, we needed to consider the interface between the hydrofoils and the other systems within the boat. For the rear hydrofoil, we needed to incorporate its articulation mechanisms close to the drive train system. We also needed to create a structural hydrodynamic member, called a 'strut', to transfer load to the hull. Lastly, the manufacturing technique involved with the hydrofoils needed to be investigated. For this project, Cedarville University partnered with SeaLandAire Technologies Inc. in Jackson, Michigan for consulting and assistance. This included aiding in the AVL analysis and the rear hydrofoil and drive train combined housing.

OVERARCHING DESIGN CHOICES

Initial overarching design choices were made based upon recommendations from Ray Vellinga (2004). From this resource we determined to have a canard configuration, larger foil in the rear of the boat and smaller foil in the front. This is due to the fact that boats normally have a center of gravity closer to the transom (back) rather than the bow (front). A weight distribution of 80 percent on the rear and 20 percent on the front was chosen to allow us to reduce drag on the inefficient, height managing front foil. This was later justified. It was also determined that the rear more efficient foil should be able to articulate each individual half foil in order to induce a rolling moment to tilt the boat and allow for banked turns.

PROFILE SELECTION

Profiles were chosen based upon lift to drag, thickness, and stall characteristics. According to Ray Vellinga (2004), the thickness of the profile should stay within 10-14%. This percentage is compared to the non-dimensionalized chord length. The aforementioned range is used in order to maintain a reasonable strength and to limit profile drag. Profile drag is a portion of parasitic drag which is a loss based upon the differential pressure around the cross section of the foil. While staying within the thickness range, it is necessary for the lift to parasitic drag ratio to be large. A “soft” stall is preferred when selecting a profile. This means that the foil experiences a gradual, rather than abrupt, loss of lift at the angle of attack where lift begins to decrease (stall). This is accomplished by foils that separate at the trailing edge first. After considering many different profiles in Xfoil, the MH115 profile (Figure 1) was recommended by SeaLandAire Technologies and was accepted. The results from Xfoil can be seen in Figure 2 compared to last year’s foil, the NACA 4412, and the original choice, NACA 6412.

It is important to note that the MH115 has a thickness ratio (maximum thickness divided by chord length) of 11.1% which is slightly less than each of the other profiles at 12% for the NACA 4412 and NACA 6412. This allows it to have the larger L/D ratio as well as its increased chamber, where chamber is the deviation of the average of the top of the profile and the bottom line of the foil from the chord line. The strength loss caused by the decreased cross section is minimal compared to the increased lift/drag ratio due to the profile change. Because of this as well as and in addition to the soft stall characteristics, the MH115 was decided upon as the profile of both the front and rear hydrofoils.

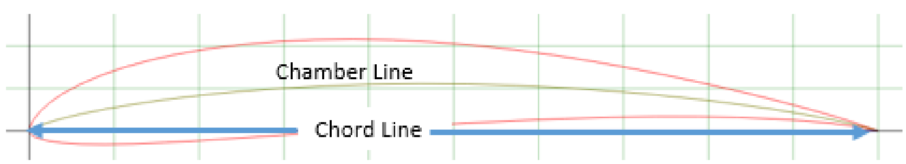

Figure 1: The MH115 profile annotated with chamber line and chord line

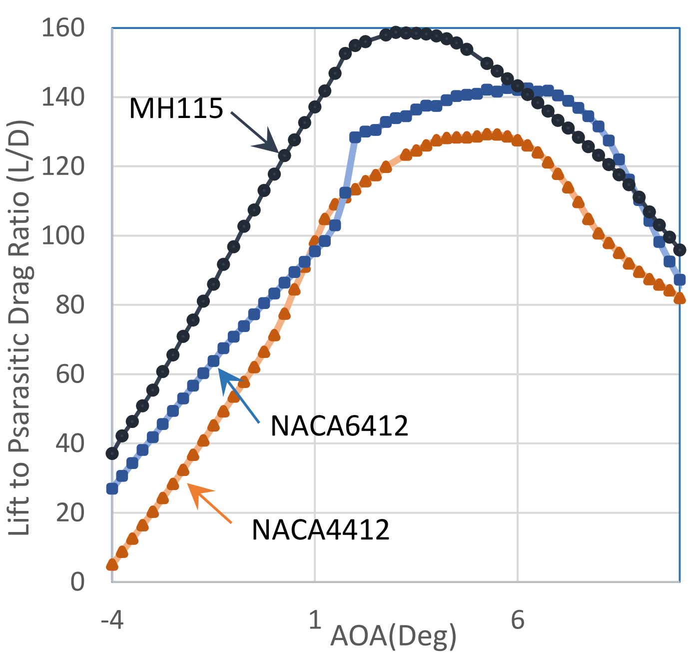

Figure 2: A comparison of possible profiles showing that the MH115 has greater L/D characteristics

PLANFORM OPTIMIZATION

The planform of the hydrofoil is the surface area projected vertically onto the horizontal plane. In order to expedite the process of evaluating different planform shapes we created a Matlab code named HydofoilGeometry.m. This code takes inputs of aspect ratio (span divided by mean chord), planform area, a choice of elliptical or tapered, profile, number of spanwise vortices (locations at which AVL calculates drag and lift characteristics, analogous to nodes in a mesh), and output file name and creates an executable .avl file. One can then open AVL, load the file, and evaluate the foil at any specified angle of attack. With the addition of a small code from Michael Kuhn, a fellow mechanical engineering student at Cedarville University, the code also exports a file that can be run using the OpenProp macro in order to export profile curves and constraint curves into Solidworks. OpenProp is an open source program typically used for the analysis of propellers and the exportation of propeller geometries to Solidworks. This portion allowed for quick modelling of the hydrofoils within Matlab after analysis was run.

The code has the capability to create a file for tapered and elliptical wings. Within each of these overarching geometries, the HydrofoilGeometry Matlab Code also has the ability to create flaps on either planform shape. The user would input a chordwise location for the hinge and a spanwise location for the beginning and end of the flap. Flaps were pursued initially as a means of varying the lift characteristics of the foils in order to takeoff. However, due to the load on the small articulation components, we decided to articulate the entire front foil and rear foil to provide a level takeoff.

According to foil theory, the optimum planform shape is one that gives an elliptical pressure distribution in the spanwise direction. An ellipse gives a span (soan) efficiency of 1. This is due to the fact that the tip of the elliptical planform goes to zero which allows for a great

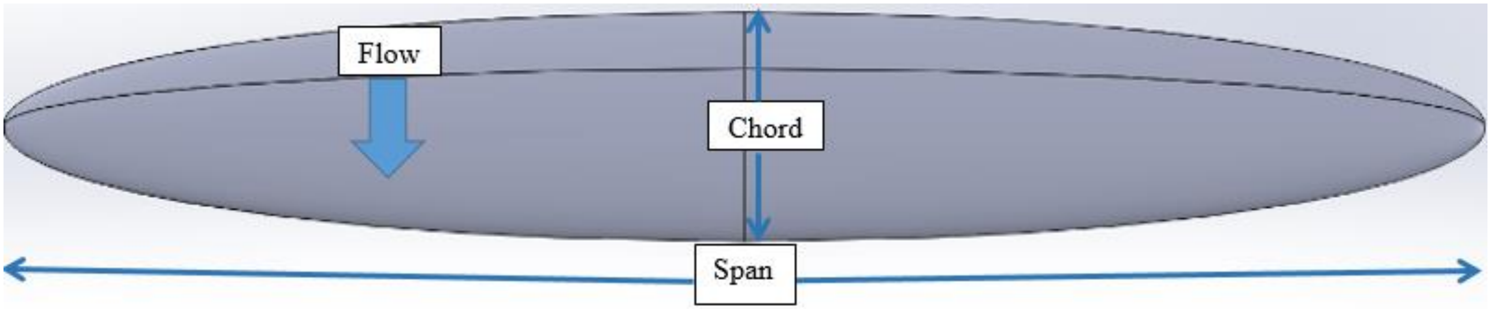

Figure 3: Solidworks top view of hydrofoil planform with general nomenclature

reduction in induced drag. Induced drag is caused by wing tip vortices, a swirling motion off of the chord at the tip of the wing causing a wake to follow the foil. The effect the wake of the front foil has on the rear foil is known as downwash. Downwash travels backwards and generally downward. Due to this, it was determined to have the front foil at a lower point than the rear foil to reduce this effect. The modelling of two foils together in Athena Vortex Lattice will be talked about in detail under the stability section. However, understanding that AVL accounts for dissipation of downwash in the chordwise direction, but not in the vertical is important when viewing the data later presented.

Upon deciding that the foil planform should be an ellipse, the planform was optimized for the given speed and lift desired. Barnaby Wainfan, an aeronautical engineer for Northrop Grumman, derived an equation for optimizing hydrofoil planform area (equation 1).

$$S = \frac{(L_r)W}{q\sqrt{C_{dow}\pi eAR}} \tag{1}$$

Where S is the optimized surface area, L_r is the lifting ratio, W is the weight of the entire boat, q is the dynamic viscosity, C_{dow} is the optimimum coefficient of parasitic drag, e is the span efficiency, and AR is the aspect ratio (span divided by mean chord). The lowest (optimum) coefficient of parasitic drag (C_{dow}) was obtained from Xfoil. The weight (W) of the entire boat was dictated by the weight budget. The dynamic viscosity (q) was determined from the density of water and the desired velocity. Span efficiency (e) is 1 due to the elliptical planform. Therefore aspect ratio (AR) and lifting ratio (L_r) are the inputs. Beginning with an assumed lifting ratio of 80/15 (rear and front respectively), it is necessary to determine the effect of an aspect ratio change on the drag and safety factor in bending. The lifting ratio does *not* add up to 100 for stability reasons that are discussed in depth in the stability section of this paper.

In order to design a foil that could withstand the forces applied it was necessary to consider strength in bending as a design parameter. An increase in aspect ratio causes the foil planform to become longer and thinner when viewing it from the top. This leads to a decrease in strength in bending. However, the longer and thinner the wing, the lower the induced drag on the wing. In order to calculate the strength on the foil, equation 2 was used:

$$\sigma_{max} = \frac{2(L)(span)}{\pi(0.75C_m)(0.85T)^2} \tag{2}$$

This equation calculates the maximum moment on the hydrofoil by taking the total lifting force on half the foil ($L/2$) and multiplying it by the centroid of an ellipse ($4b/3\pi$, where b is the span of the half foil). It then calculates the section modulus by approximating the foil to be a box beam. To make this approximation the mean chord (C_m) was multiplied by 0.75 and the thickness (T) by 0.85 to estimate the sides of the "box" according to the suggestion of Besnard, et al (1998). This equation was placed in the HydrofoilGeometry Matlab code in order to further increase its ability and output.

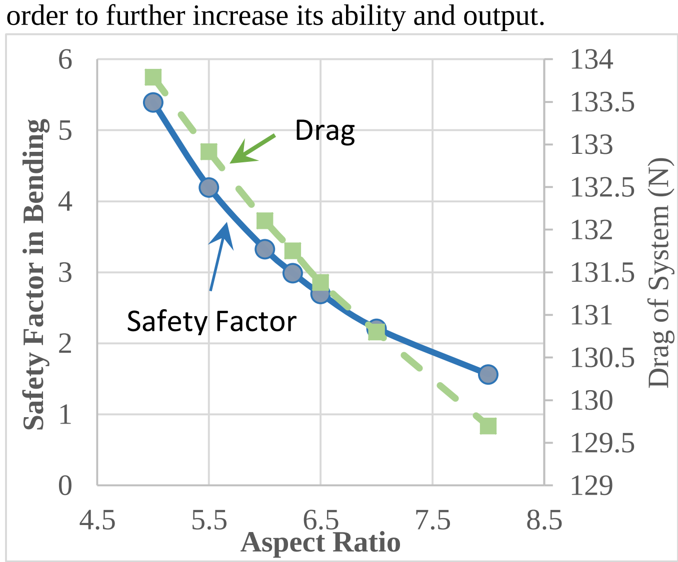

Figure 4: A study showing an increase in front foil aspect ratio causes a decrease in drag and strength

The effect of a front foil aspect ratio change on the drag of our final hydrofoil system as a whole can be seen in Figure 4. It is important to recognize that a change in the aspect ratio of the rear foil would affect the overall drag more significantly than the smaller front foil which is only responsible for 20% of the total lift.

From this study and the fact that our design could reasonably see three times the normal lift if the foil went to a high angle of attack due to a glitch in the control system, the aspect ratio was determined to be 6.25, which allowed for a safety factor of 3. To increase efficiency of the rear foil, the aspect ratio was determined to be 8.25. The lift of the front foil is taken out by the wings being fixed to the front pod. However the rear foils are attached differently. The load transfer of the rear foils will be talked about under the rear assembly design section.

Based upon these things the entire system was evaluated for drag at a constant lift equaling the weight of the boat over an operable range of angle of attack. This can be seen in Figure 5. The reasonable angle of attack range, from -6 to 13 degrees, is dictated by staying below stall angle of attack (AoA) and having the ability to pull the boat into the water quickly if the need arises. The maximum amount that the boat can pitch either direction is 6 degrees. Therefore the angle variation needed is between -12 and positive 19 for the foils.

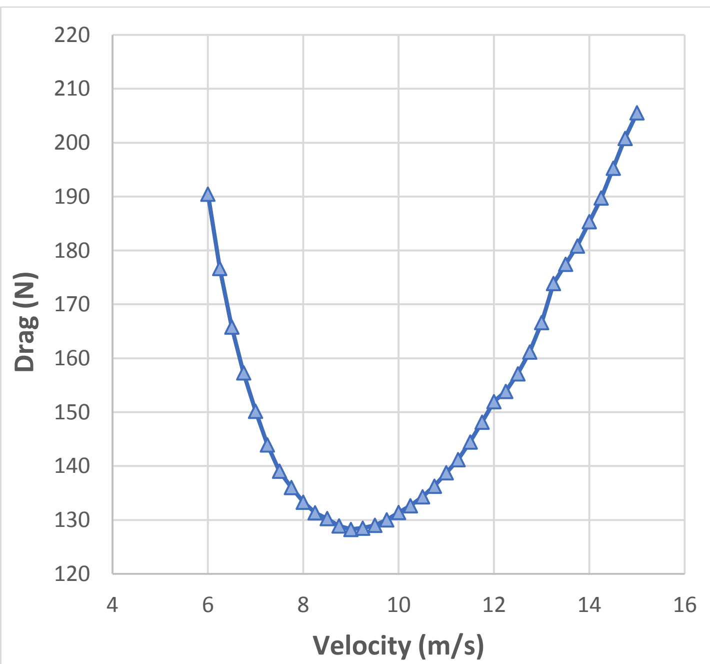

Figure 5: Final drag curve for entire hydrofoil system, including hydrofoil parasitic and induced drag, interference, pod, and strut drag

STABILITY

Within the realm of hydrofoil control and stability there are 2 subcategories that will be examined: height/pitch and steering/roll management. Stability will be assessed by the boats ability to return to its trim state, or the state where there are no net moments acting on the boat. We must design a canard system where the front foil controls the pitch and the rear foil controls the roll. During turns, we must design a boat that can bank based on the speed and radius of curvature.

The bow foil must be able to increase and decrease the pitch of the boat in order to achieve an equilibrium altitude when foilborn. In order to achieve this, we must allow the bow foil to reach the AoA required for takeoff, which is limited by the foil stall angle. The stern foil must also be able to change the pitch of the boat during take-off (to perform a level take-off) as well as provide differential deflection (aileron) for roll control. The stern foil will need to have a range of motion similar to the bow foil, in order to provide the system with its maximum potential rolling moment, limited only by the stall AoA.

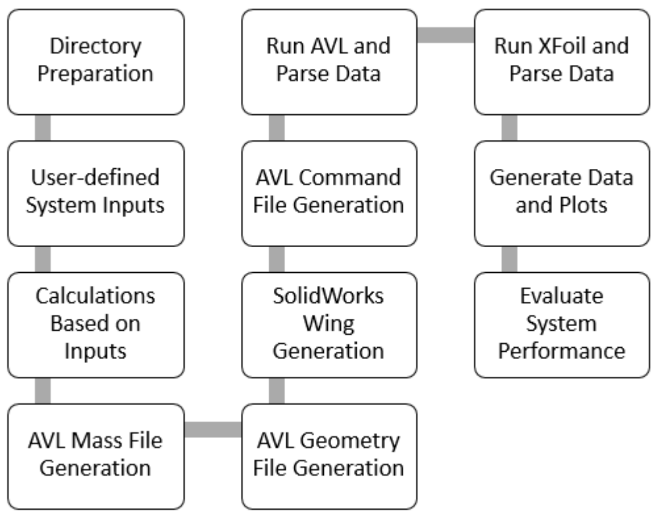

Figure 6: HydrofoilFlight.m flowchart

We developed a Matlab code, HydrofoilFlight.m, to study drag and stability, among other system characteristics, during takeoff, cruise, sprint, and maneuvering. It runs AVL and Xfoil (Fortran programs developed by MIT) and parses all flight, stability, and drag data into Matlab for analysis using plots (shown below). This code has been instrumental for most of our design choices regarding pitch control and pitch stability, and is still being developed to model data pertaining to the maneuverability of the hydrofoil boat. It is mainly used to study stability and drag data, but will also give us data pertaining to the deflections of our canard foil and our rear half foils, bank and pitch angles that result, and turn radius and slip during flight (which are currently based on bicycle dynamic equations). The general process of this code is given in Figure 6.

Horiuchi's book Locus of a Boat Designer 2 played a major role in our research. In the Canard design, an increase in AoA of the front hydrofoil dictates the pitch of the boat. As the bow rises out of the water, the stern hydrofoil pitches up, increasing its AoA, and raising the stern out of the water automatically. Another option is a coordinated takeoff where the AoA of each foil is controlled separately to take off while staying level. There were several proposals as to how to regulate the equilibrium height of the boat out of the water. The problem here is that at higher speeds, the bow hydrofoil has to be controlled within a single degree, and this is too difficult to be done manually. The best of these options seems to be an ultrasound sensor at the bow hydrofoil facing the surface of the water from underwater to gauge hydrofoil depth. The benefit of this is twofold. It would limit the interference of the splashing from waves above the water, and it could be more responsive since sound travels much faster through water rather than air. The other practical option is a mechanical surface skimmer that monitors where the water level is in relation to a set point on the bow strut. An automatic system must be in place to maintain the ideal height above the water, especially considering high speeds. We chose to use a mechanical surface skimmer due to cost and simplicity.

In order to ensure pitch static stability in our system, there are 2 points in the system that have to be forced to be in certain locations. The first point is the center of gravity of the boat, and the second point is the neutral point.

Pitch stability is strongly affected by the location of the neutral point (NP) relative to the system center of gravity (CG). The neutral point is defined as the location between the lifting surfaces where the pitching moments cancel out. Static pitch stability is introduced into the system by placing the CG fore of this NP, inducing a net negative pitching moment and pushing the bow down. The NP must not be too far behind the CG, otherwise the system will not be able to hold the bow up; whereas if it is fore of the CG, the system would pitch up, increasing the foil AoAs, increasing lift, and causing an unstable pitch loop.

All sub-systems on the boat have to be placed in such a way that the center of gravity is located where necessary to produce static pitch stability. Stability is necessary during takeoff as well as flight. As the hull sits in the water, it has a center of buoyancy, or the centroid of the mass of water displaced. In order for the boat to be level when sitting in the water or while cruising across the lake, the center of gravity has to be located near the center of buoyancy.

When flying on foils, the center of gravity has to be fore of the neutral point to induce a net negative pitching moment, which tends to pull the bow down into the water when the system is perturbed. Since the neutral point is based on the lift of the foils, the surface areas and the strut locations have to be designed to allow the neutral point to be aft of the center of gravity. The distance from the neutral point to the center of gravity is called the stability margin when normalized by some system geometric parameter. For this case, the desired stability margin was between 50% and 200% when normalized to the rear wing root chord, where 50% is more maneuverable and less stable and 200% is more sluggish and more stable. Since an acceptable stability margin is not well known for hydrofoil boats, these values are estimates made by SeaLandAire from their experience with building flying systems and are somewhat determined by how comfortable the skipper is with maneuverability.

The load distribution has been constrained to 80/20 based on SLA suggestions and previous work. This number is somewhat arbitrary and can be changed if necessary for layout constraints. When the foils are lifting the boat's weight, 80% of the boat weight falls on the rear foil while 20% falls on the front foil. A lower distribution on the front foil makes the system more efficient because the front foil is tasked with pitch and height control, often driving it to higher angles of attack to produce the necessary lift and causing more drag. Driving the front foil surface area to be smaller by placing the center of gravity more aft creates less induced drag and less downwash, but will likely reduce response time/possibly become unstable.
Once we have determined the masses and locations of centers of gravity of the key components (or have an estimate based on our weight budget), the system center of gravity is calculated and forced to be near the boat center of buoyancy by moving the location of the skipper. We control the neutral point location by moving the strut locations or changing the surface areas of the foils. We determined the max distance between struts to be 5 meters to limit the max pitch of the hull and to provide room for the center of gravity to shift due to skipper movement or water in the hull, without becoming unstable. The foil surface areas are being optimized for drag using Wainfan's equation, but are given a desired lifting force for each foil. A lifting

distribution, as opposed to the loading distribution, is specified to be 80/15. Intentionally designing the front surface too small drives the neutral point aft and ensures pitch static stability if the loading distribution is 80/20. It also drives the front foil angle of attack higher to provide the extra 5% lift necessary to keep the boat level.

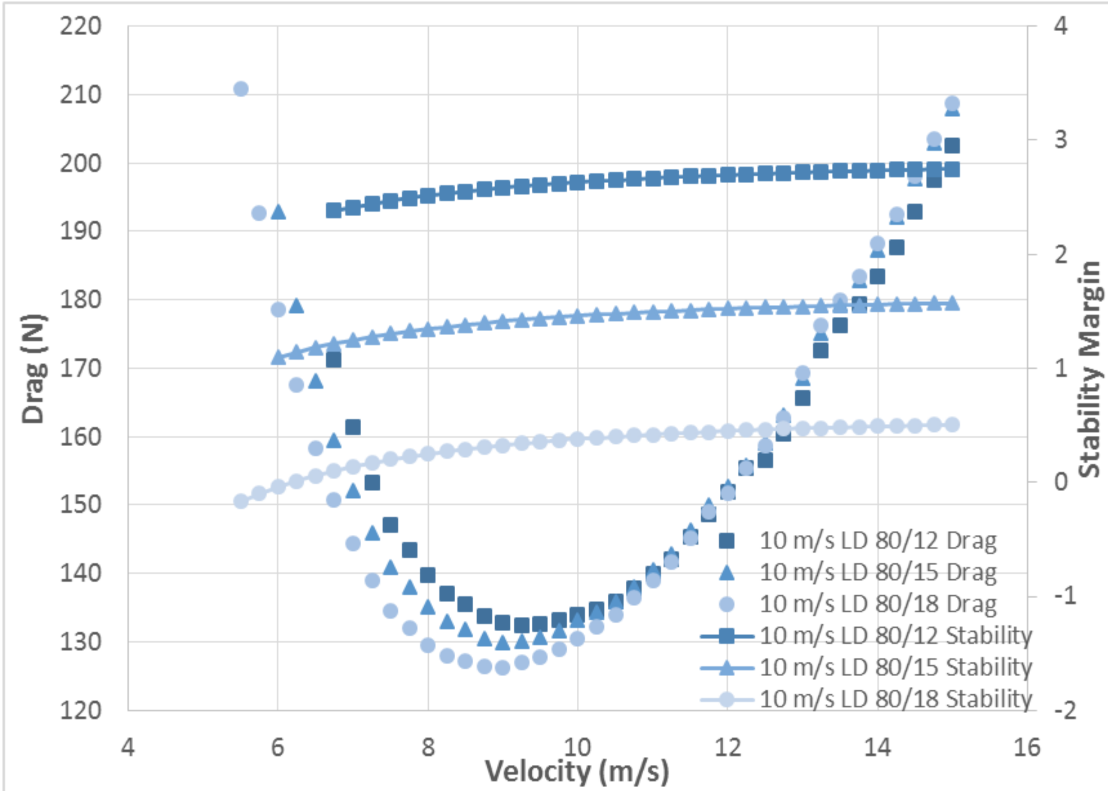

Figure 7: Front foil lift distribution study to determine the effect of surface area changes on drag and stability

Often, a design is a tradeoff between stability and drag. While running AVL (inside HydrofoilFlight.m), we found that the stability margin varies with velocity and with system angle of attack, as does drag. In order to test our understanding of system performance and come to a conclusion regarding final planform geometries and other system geometry specifications, we created a series of studies for drag and stability. Studies were performed using HydrofoilFlight.m, which we developed this year to better understand the trimmed flight conditions (banked or unbanked, turning or straight, takeoff, sprint, etc.…) of our boat. Our control case was always done while not turning with an 80/15 lifting distribution, an optimal velocity of 10 m/s, and a foil separation of 5 m. The studies we performed were the effect on drag and stability of a surface area change of the front foil, of an overall lifting design, of optimizing for a different velocity, of washout/in of the foils, and of foil separation distance. The takeoff speed is defined as the slowest we can go such that the foils can still provide the lift needed to lift the boat out of the water without individual foil angle of attacks reaching past their stall angle. The sprint speed is limited by the total thrust available from the propeller and the logical optimum cruise speed is where the drag curve is minimum. Another constraint that we place on these studies is that the boat is in trimmed, level flight for all data points. The front foil AoA is set in AVL to ensure there is no pitching moment while the rear foil AoA is set to ensure that the boat is level (the system AoA is 0). This constraint is applicable only for level takeoffs. SLA is building the control system and software to perform level takeoffs, yet further discussion is needed to determine if the system will attempt to keep the boat at a constant AoA during maneuvers.

The first study we did is the effect of a surface area change on the overall system drag and stability. The drag and stability curves are shown in Figure 5.1. As the surface area of the front foil decreases, the drag increases before the optimized speed and decreases after the optimized speed. This is due to the front foil having to run at progressively higher angles of attack at lower speeds, which also causes our takeoff speed to increase, and at an AoA closer to optimum at higher speeds, causing our max sprint speed to increase. The curve shifts up as it shifts right as well. This is due to the non-foil drag which is pushing the curves upward. The other portion of interest is that as the front surface area decreases the stability increases and vice versa. This is due to a decrease in loading on the front foil, pushing the neutral point farther aft of the center of gravity. The stability curve is also non-linear because the center of gravity is far above the neutral point, causing static instability. We have chosen a lifting ratio for the front foil of 15% due to the stability and relatively low drag it offers.

The second study we performed is the effect of the lifting distribution on stability and drag. The drag and stability curves are shown in Figure 8. We find that as you lift the system more towards the front of the boat, the stability decreases and the drag decreases. All reasons for the curves shifting with a change in lifting distribution hold true from the first study. A lifting distribution of 80/15 is still the ideal balance between drag and stability.

The third study we did is the effect of designing for a different optimum velocity, which scales both surface areas with the same lifting distribution. The drag and stability curves are shown in Figure 9. As the optimal velocity increases, the minimum drag obviously shifts towards the higher velocity. The drag curve also shifts up as you optimize for higher speeds due to the strut, interference, and pod drag incurred at those higher speeds. The stability margin also increases more with speed as you optimize for higher speeds due to the foils' surfaces areas getting larger. The cruising speed of 10 m/s is our goal in the DSC race, and it give us a takeoff speed of about 6 m/s. As we optimize for a lower speed, the takeoff speed decreases due to an increase in both surface areas, proportionally, allowing them to run at lower angles of attack for the same lift.

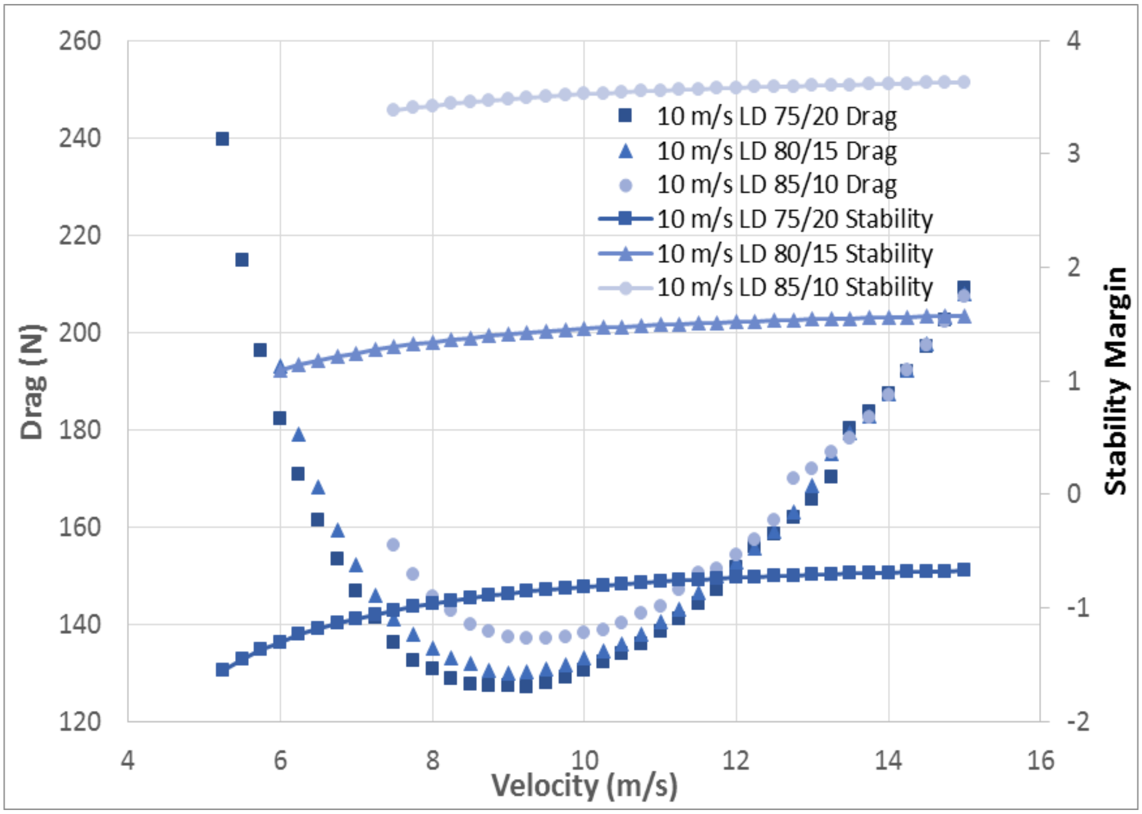

Figure 8: Front foil lift distribution study

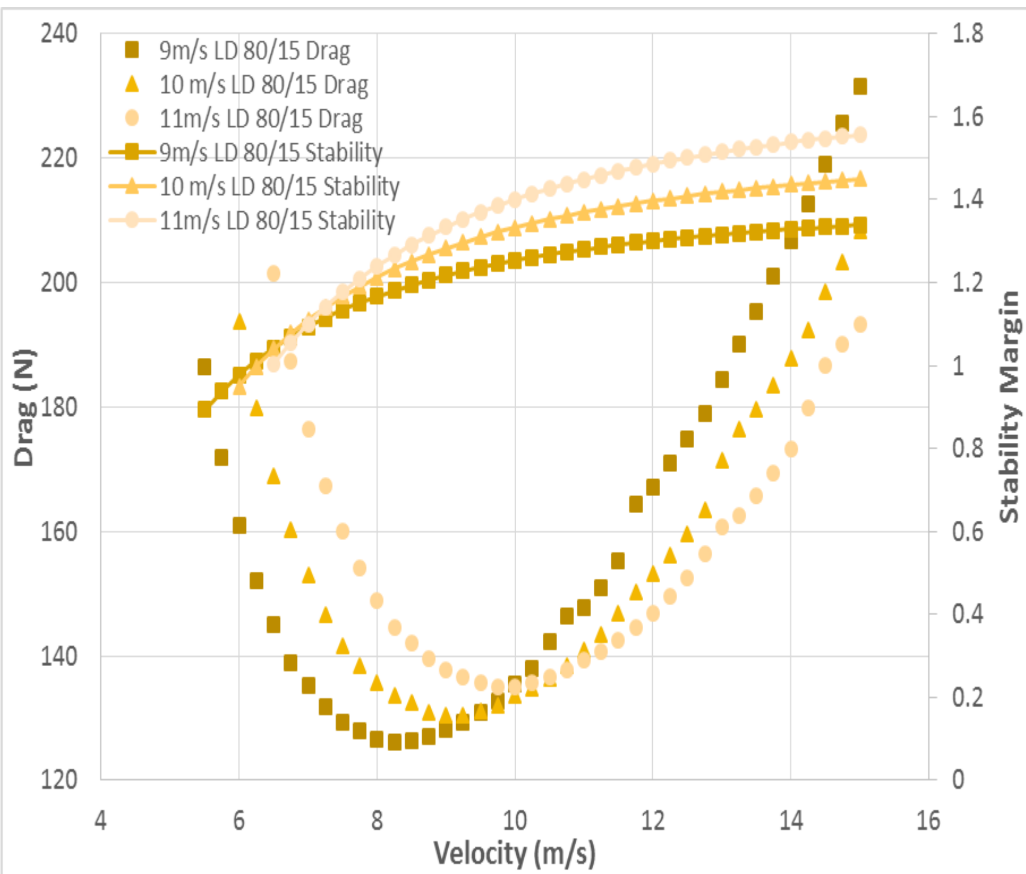

Figure 9: A study on the effect of changing the optimum velocity input into Wainfan's surface area optimization equation

The fourth study we did is the effect of washout/washin, which changes the angle of twist of the wing across the span (decreasing/ increasing the AoA respectively), on drag and stability. The drag and stability curves are shown in Figure 8. As we add washout to the foils, stability is only affected as much as the lift from each foil is affected, which is negligible. Washout helps to reduce the induced drag from the vortices near the tip of the wing, so the system drag is overall less. We have found that washin (the inverse of washout) is not beneficial except to lower drag at takeoff, so this case is not being considered. Due to only a marginal tradeoff of drag before and after cruise with washout, we are going to design the foils with no washout.

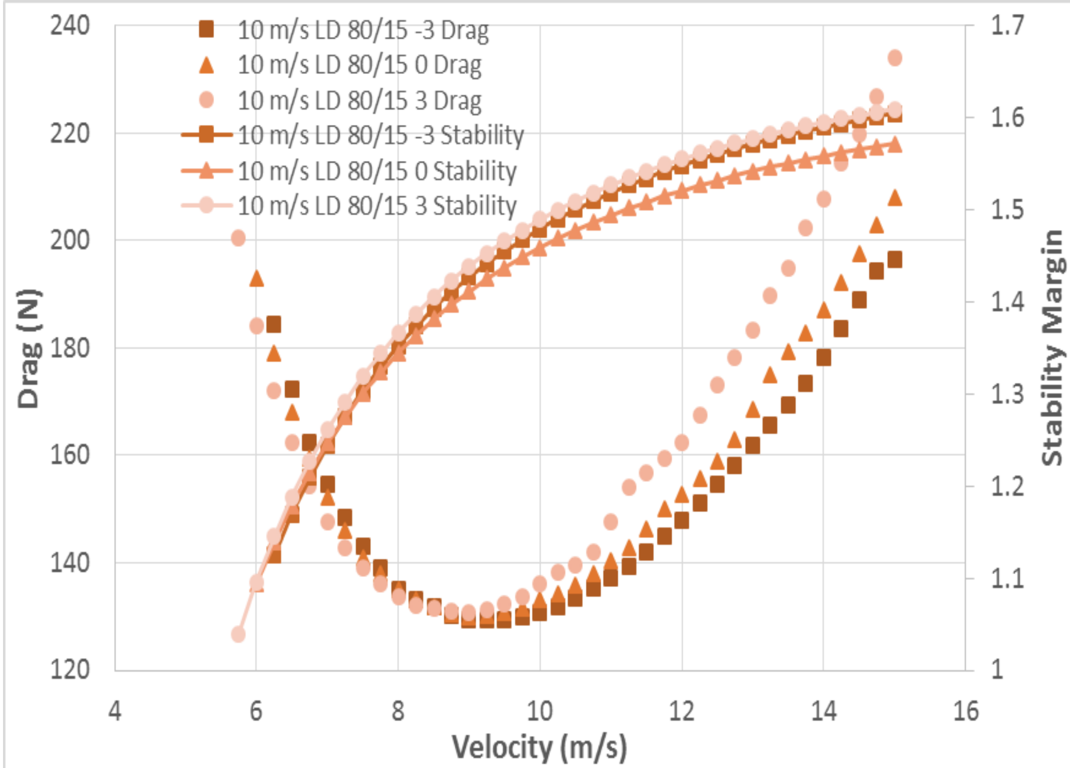

Figure 10: Washout/washin study showing that washout has a positive effect after the ideal speed and washin has a negative effect after this speed

The fifth study we did is the effect of the foil separation distance, which will theoretically change the sensitivity of the system because center of gravity movement has less of an effect on the stability margin with farther spaced foils. The drag and stability curves are shown in Figure 11. As we increase the separation distance there is virtually no effect on drag in the system while the stability increases. This shows that the system will be less sensitive and more stable the farther apart the foils are. Based on this information, we will force the separation distance as large as we can within our system geometry, which currently is 4.8 m.

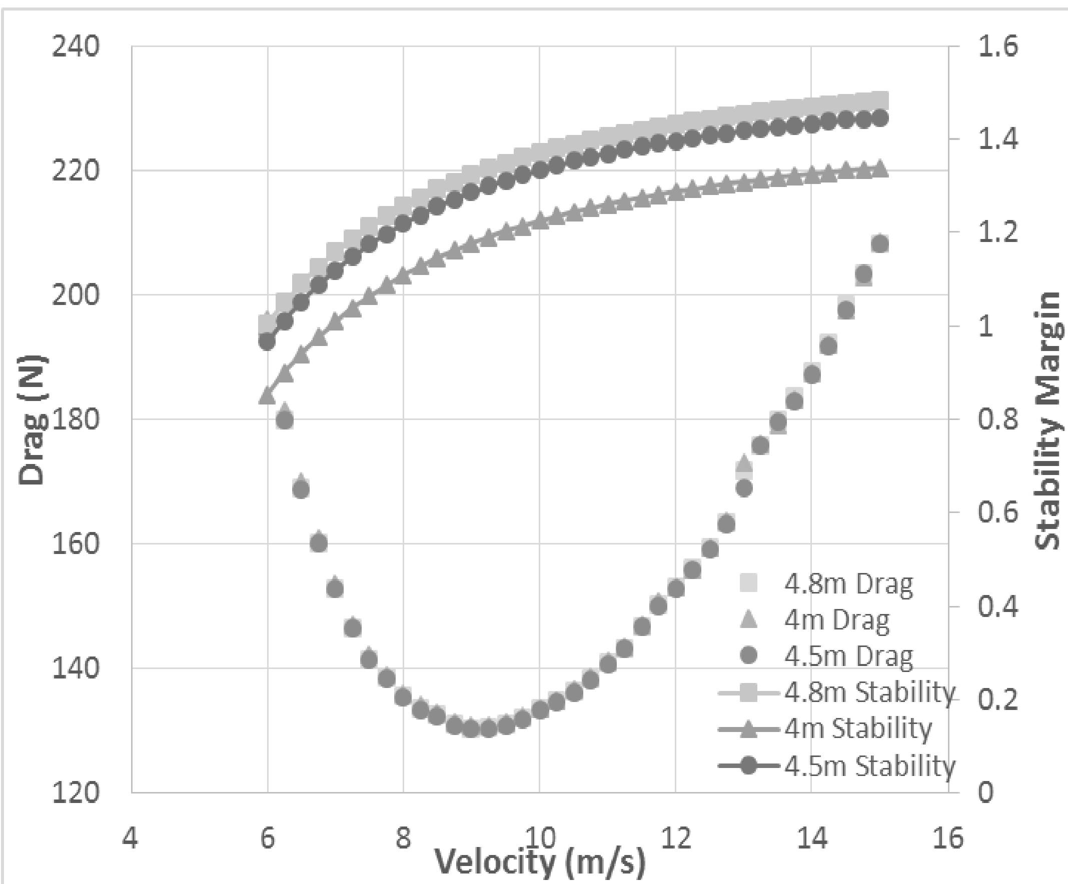

Figure 11: Foil separation shown to affect stability much more than drag.

STREERING (YAW/ROLL) CONTROL

In steering, Horiuchi was obsessed with creating the ideal banking angle, where the centrifugal force does not shift the driver in either direction, but the net force vector pushes the driver into his seat. The ideal banking angle is a function of speed and turn radius. When steering canard system, usually the bow strut is rotated much like riding a bike. Figure 12 shows the moments on a foilborn boat induced by turning the front hydrofoil like bike handlebars. The problem incurred from this steering method for Horiuchi was that the boat was yawing too much relative to its rolling. They found that this was due to the center of gravity being too far aft. Since they could not change the center of gravity, they decided that rotating the stern strut at ¼ the rate of the bow strut would provide enough of an element of vector thrust (since the motor and propeller were mounted above the stern hydrofoil) to reduce the rolling component of the moment arm adequately. Vector thrust is caused by turning the rear

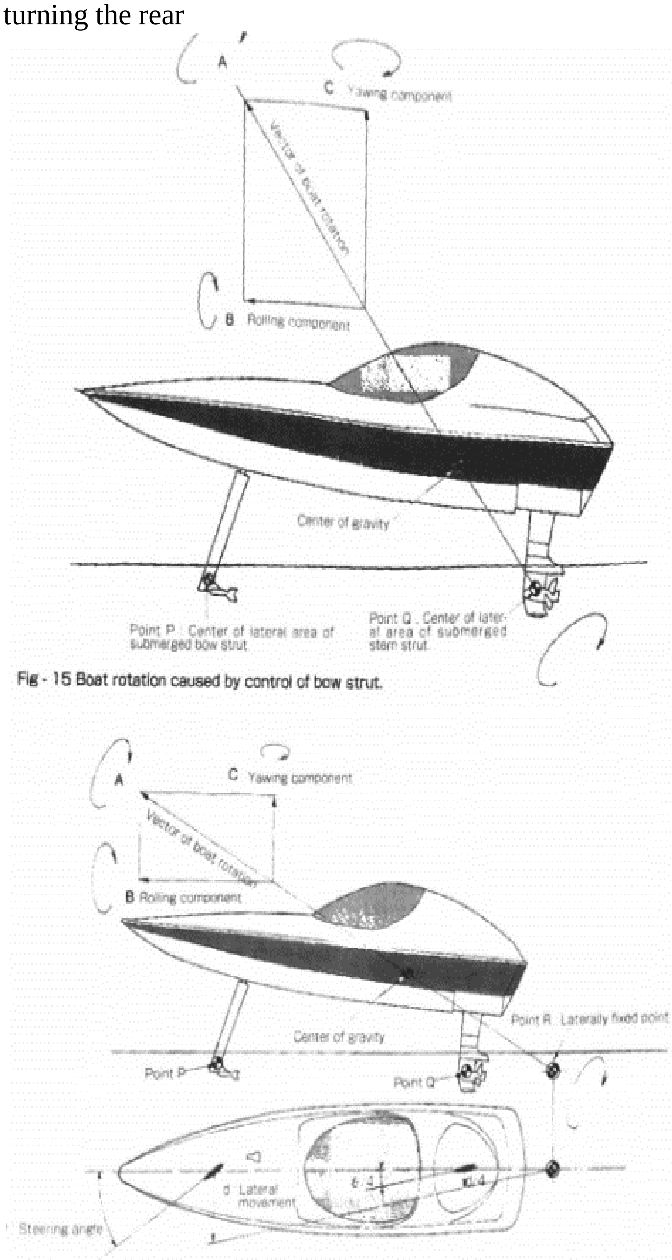

Figure 12: Locus of a Boat Designer 2, p. 126

strut. This increased the yawing and decreased the rolling to the inside, resulting in a flatter turn. The net boat rotation vector will intersect with the center of gravity and some laterally fixed point. This point is realized by the intersection of the vector determined by the lateral movement of the front strut and the rear strut, and the centerline of the boat. In the top diagram, that point is on the rear foil because it didn't move. In the below diagram, that point has shifted back into the water because the propeller was set up to provide vector thrust, inducing more roll.

Vellinga also brings forth the idea of turning under the fall. This phrase is normally used for bicycles. When a bike is initially turned one direction it begins to fall the other direction. If the bike is allowed to continue the curve beyond the path of the boat the centrifugal force will desire to right the boat. This concept is called over tracking. If this could be accomplished, it would remove the need for active roll control.

Using HydrofoilFlight.m, we are able to make surface plots that show the relationship of the stability, drag, bank angle, and pitch angle to velocity and amount of turn on one or both struts. So far, we have decided and have been modeling vectored thrust due to the desire to have a maneuverable boat when we are not flying. As previously stated, we are considering forcing the system pitch to 0, at least for takeoff. We modeled the system to allow for a pitch change in Figure 11-15. Each of these plots show a mesh grid of points outputted from AVL and a surface regression between those points.

Figure 13 shows a more variable stability margin related to velocity due to the ability of the system to pitch. As previously mentioned, both drag and stability margin are heavily affected by system AoA.

Figure 14 shows a drag surface as it varies mainly with velocity. We notice that allowing the system to pitch decreased the drag at cruise by about 15-20 N. This is the common tradeoff with stability since allowing the system to pitch made the boat unstable at certain speeds.

Figure 15 shows the bank angle as it varies with velocity and turn of the rear foil (vectored thrust). We noticed that with only a 5 deg turn, the boat will trim to about an 11 degree bank at cruise, which is under the geometric max bank angle of about 20 deg.

Figure 16 shows the pitch of the boat as it varies mainly with velocity. We noticed that as the boat is required to pitch up at lower speeds to provide the necessary lift, it is required to travel faster than 6 m/s so as to not exceed the maximum possible pitch angle of 6 deg based on system geometry.

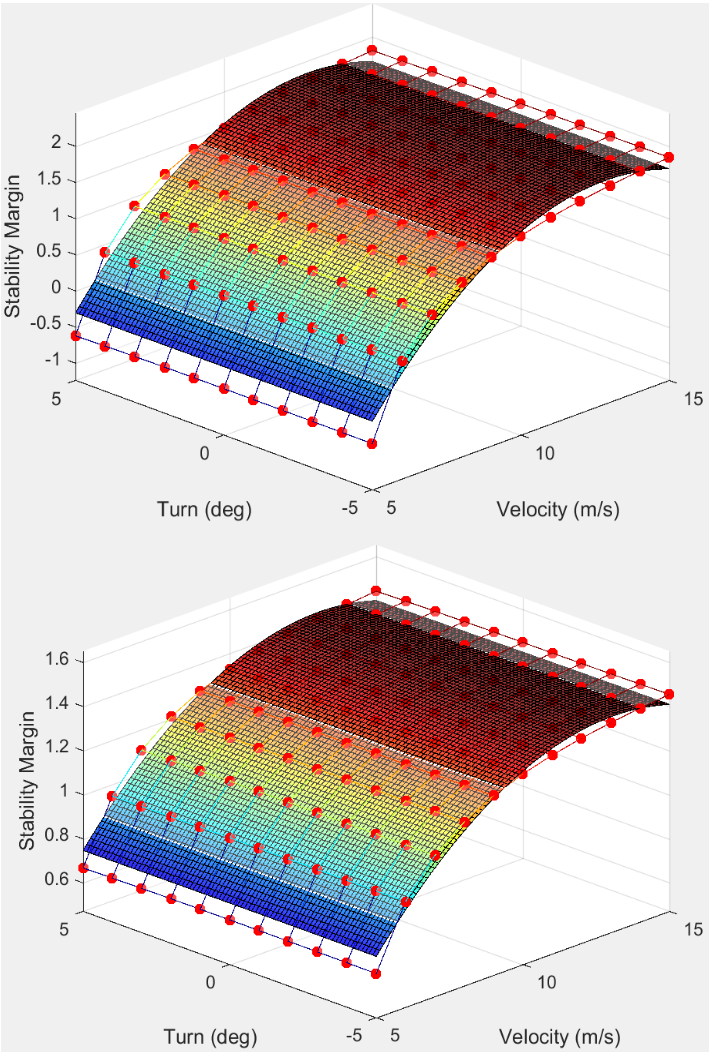

Figure 13: Stability margin variation with velocity and turn with/without pitch (upper graph/lower graph)

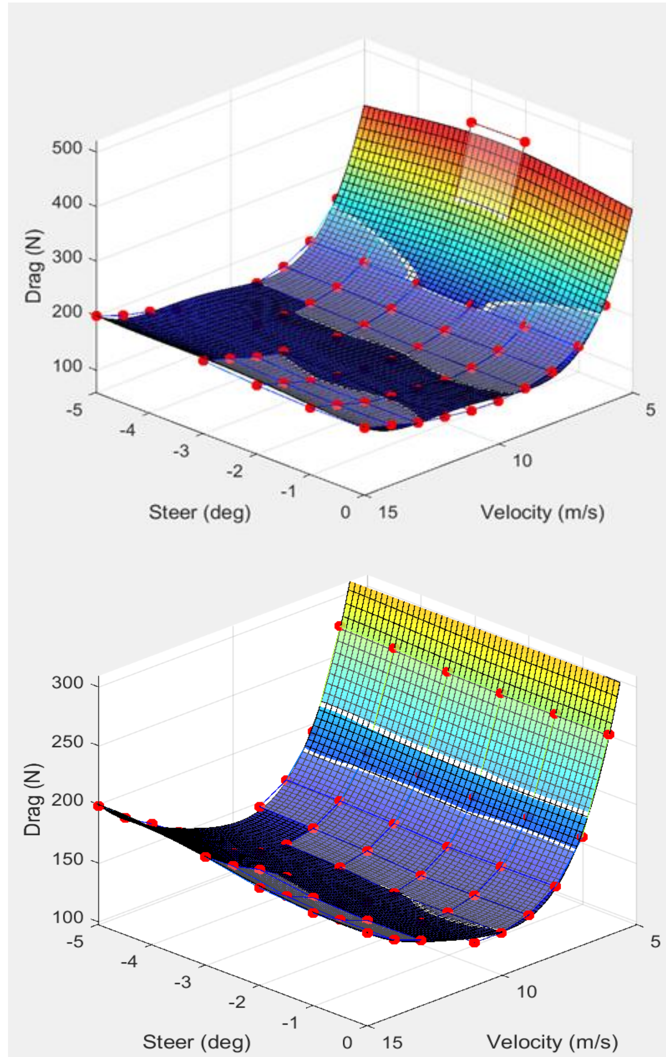

Figure 14: Drag variation with velocity and turn with/without pitch (upper graph/lower graph)

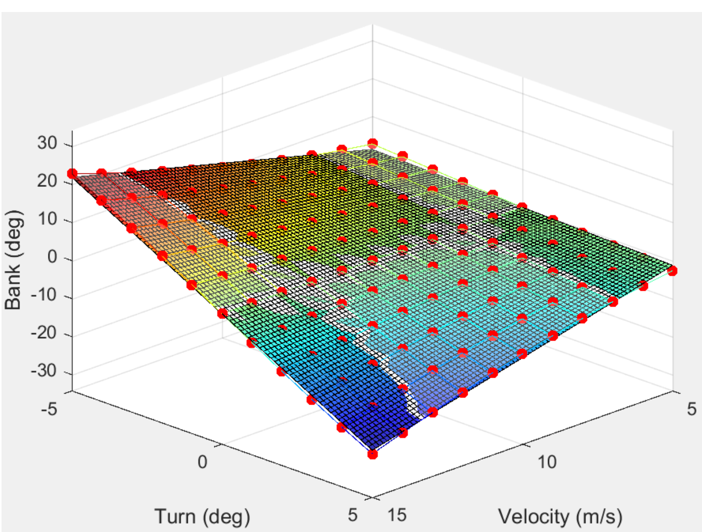

Figure 15: Bank angle variation with velocity and turn

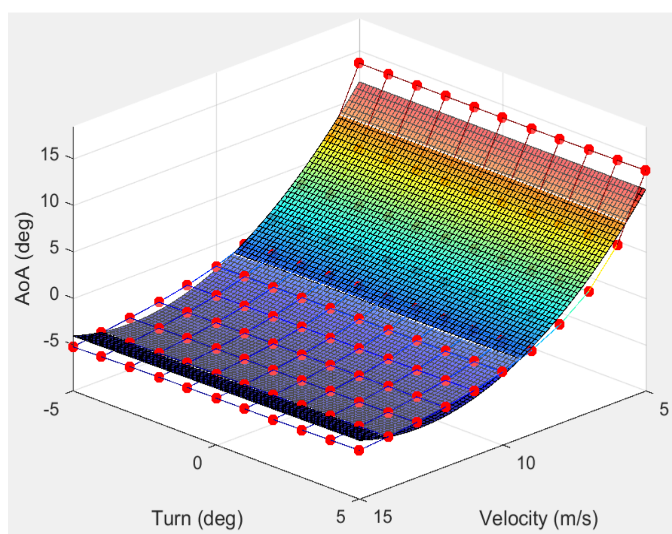

Figure 16: System AoA variation with velocity and turn

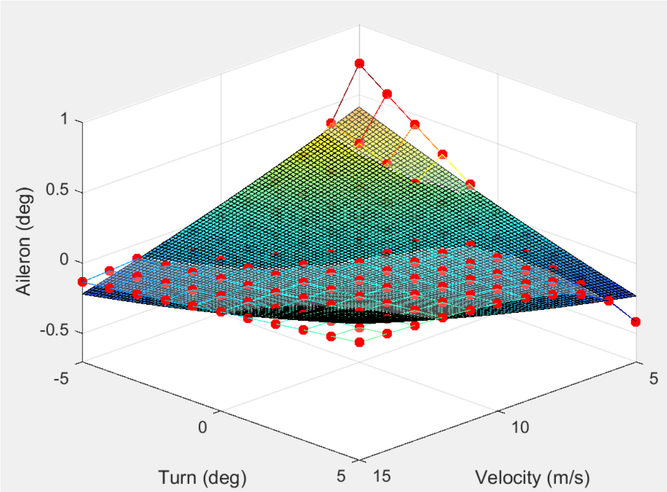

Figure 17: Bank angle variation with velocity and turn

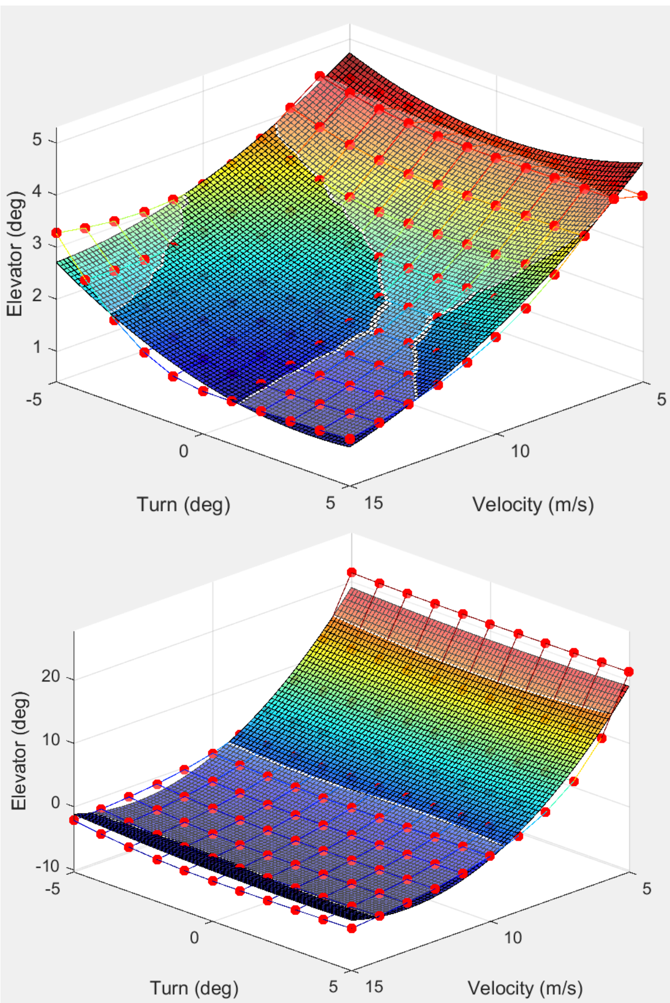

Figure 18: Front foil deflection variation with velocity and turn with/without pitch (upper graph/ lower graph)

Figure 17 shows the required individual rear half wing deflection at different speeds and turn angles to cancel out the rolling moments. We note that the maximum deflection that the half foils will see is around 1 deg, much less than our geometric constraint of 10 deg.

Figure 18 shows the needed front foil deflection to provide the lift necessary to cancel out the pitching moments. As seen on the right, naturally when pitch is constrained to be level, the elevator has to deflect much more to cancel the pitching moments. The minimum speed the foils therefore can go is limited by the stall AoA, which is around 13 deg. This allows the foils to run at around 6 m/s and still provide the necessary lift to fly.

FRONT FOIL ASSEMBLY DESIGN

The key design consideration of the front foil was to consider the method in which the foil would change angle of attack. Due to the fact that the foil as a whole would be articulated the problem became much simpler in comparison to the rear foil articulation. This allowed for the foil to be attached at the root to a fairing interface between the foils and the strut.

The final design for the front lower hydrofoil assembly can be seen in Figure 19 and 20. The design works by transferring the load from the foils to the plastic bushings through the bracket to the strut, which transfers the load to the hull. The actuation rod pulls the foil to the correct angle of attack. The rear pod and hydrodynamic cover are both for flow purposes only and rotate with the entire foils and pod. The hydrodynamic cover maintains the best drag shape at our cruising speed of 36 km/hr. The screws were chosen and found to have a safety factor of 7 under normal operating conditions.

The pod shape was made using a rotated and extended profile of the strut. According to Hoerner's Fluid Dynamic Drag, the pod should be two times the length of the longest member at the intersection in order to reduce interference drag. Interference drag essentially accounts for the drag loss from having two separate entities combined into one. The final pod design was shortened for machining purposes. This allowed for the pod and foils to be machined together out of a 1 inch thick stock of aluminum. Due to this, the part is more simply made and easier to repeat. The pod also allows

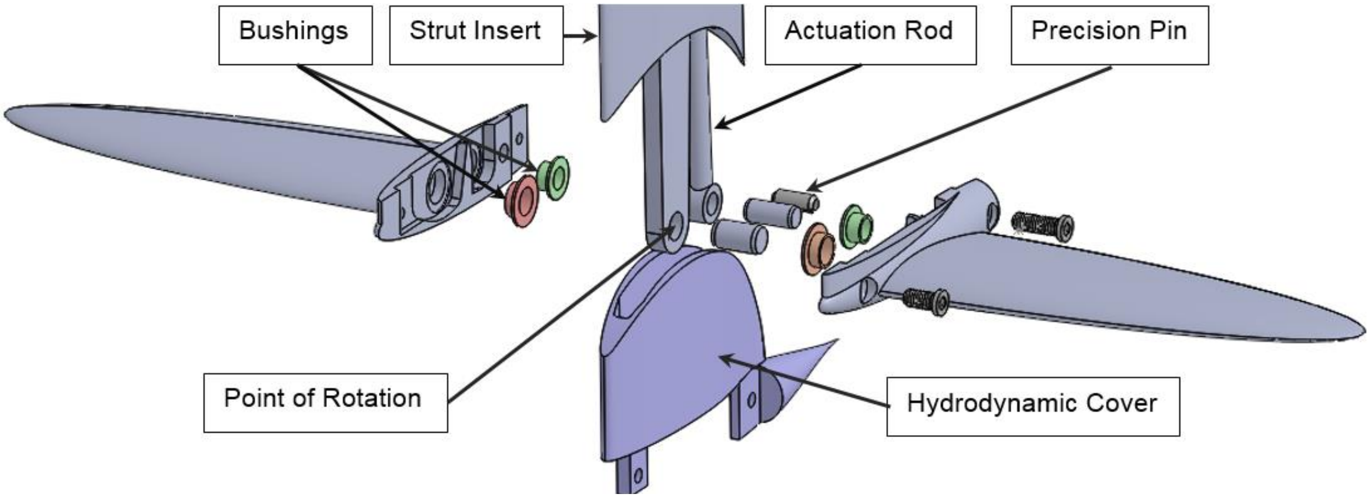

Figure 19: Exploded view of front hydrofoil assembly

for extra space for the rotation point and pivot pin. With the outer geometry, chosen having the pivot point in the pod allows for the thickest bracket for load transfer. If the pivot point was in the strut, the strut would experience large eccentricity of load due to center of pressure moving with a change in AoA.

The center of pressure is quite important to the conversation of design as well. This is the location through which the resultant lifting force acts. This location moves with change in AoA. Although the aerodynamic center is a good approximation of the location through which all forces act (25% of the chord from the leading edge), it is not exact. In order to determine the location of the coefficient of pressure we took the pressure gradient found from Xfoil over a range of angle of attack and numerically integrated over the curve. We then took that value and numerically integrated over the planform of the foil due to the fact that the chord length changes as the planform changes. The change in center of pressure over the operating range of angle of attack can be seen in Figure 21. It is desirable to have the actuation rod maintain force in one direction so as to reduce any sort of play in the system. This is due to the fact that whenever the pull rod would switch from tension to compression, or vice versa, the wing could flutter. In order to account for this and to ensure strength the actuation rod was placed in tension over the range of AOA by having the point of rotation be fixed at 25% of the chord from the leading edge.

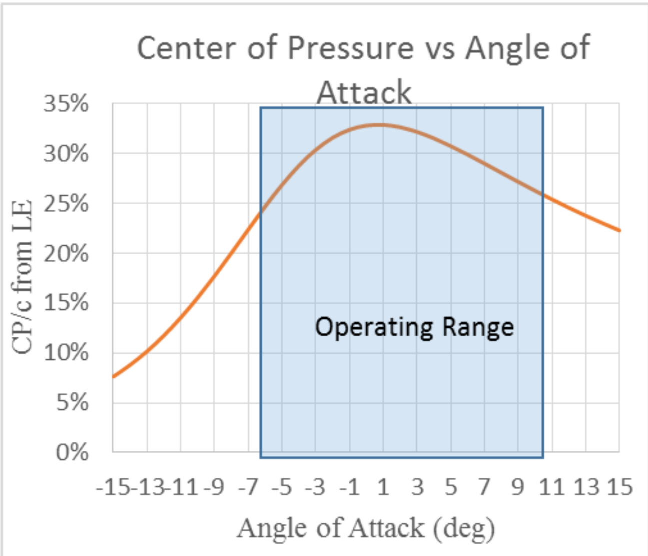

Figure 21: The Operating Range of Angle of Attack is shown to show the Variation in Center of Pressure over a Range of AOA

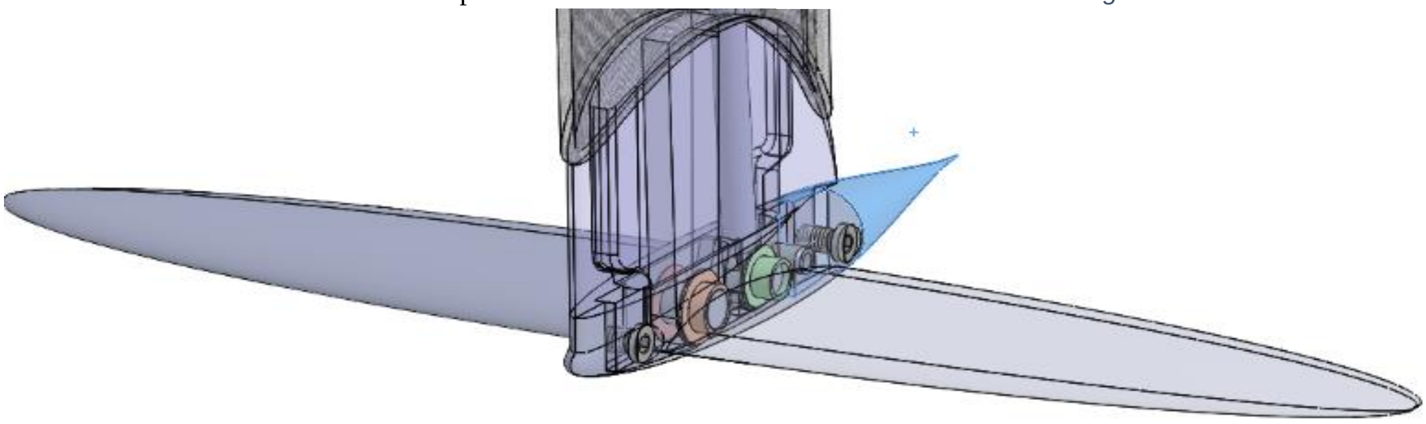

Figure 20: Collapsed view of front hydrofoil assembly

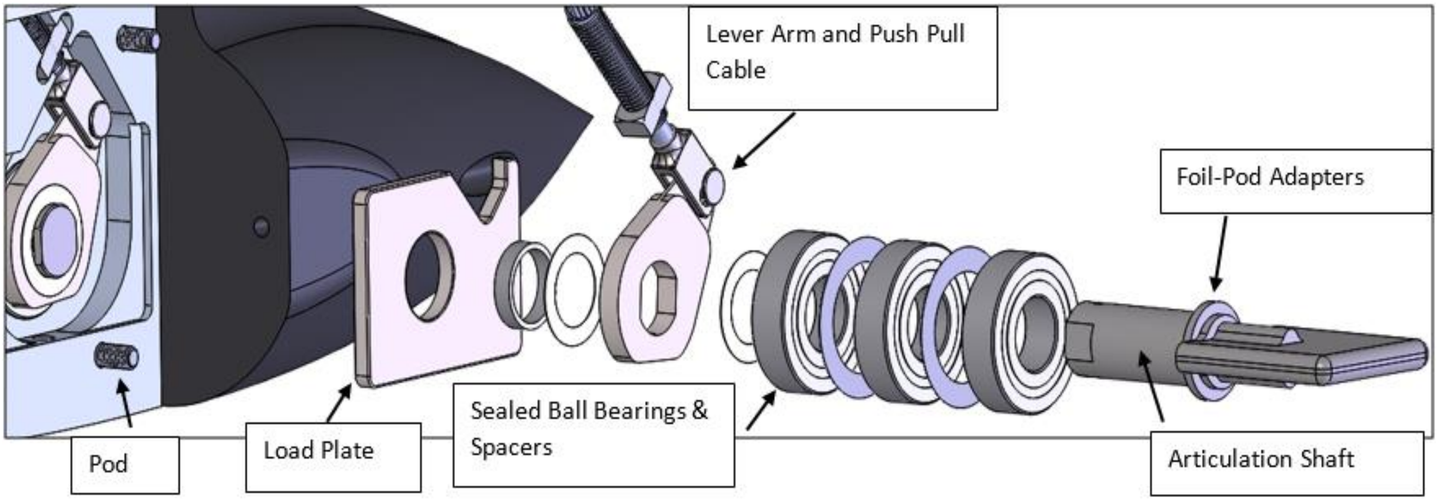

Figure 22: Exploded view of hydrofoil articulation system

REAR FOIL ASSEMBLY DESIGN

The purpose of the rear hydrofoil assembly is to control roll while in flight. Three primary areas of concern in this work are designing a mechanical system for roll control, combining foil and drive drain compartments and manufacturing the pod.

A key design in our work was a mechanical system for controlling the roll of our boat while flying on hydrofoils. (Figure 22) This system is located in the rear pod behind the propellers. This mechanical system involved the following three areas: 1. Foil control surfaces, 2. Load transferring components, and 3. Articulation components. The information presented here consists of the significant design choices and the final design.

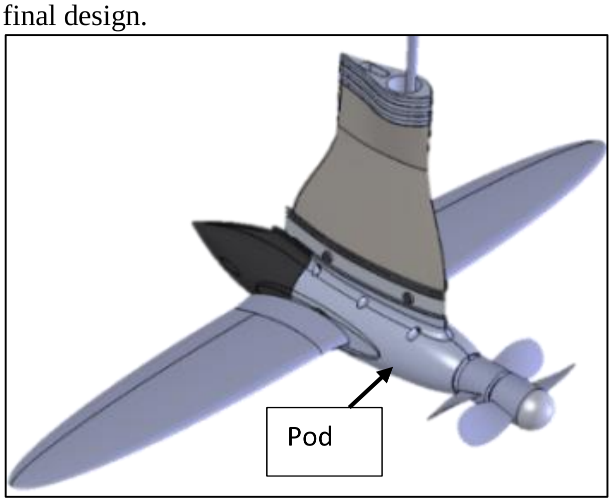

Figure 23: Final rear drive train, strut, and hydrofoil assembly

The discussion of these three design areas will begin with the final design and will proceed with how we choose each of the components of this design. (See Figure 23. Final Design)

In Figure 22, we have displayed the four primary components of this system. The load plate, bearings, and paddle are the load transferring components. The paddle, lever arm and push-pull cable are the articulating components.

Foil Control Surfaces

Initially, we chose flaps for our control surfaces (Figure 24). After a flap analysis and prototype development, we changed our control surface design to full foil articulation.

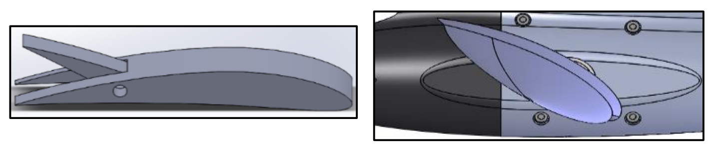

Figure 24: Hydrofoil flap concept (left) with final articulation design (right)

Our flap analysis showed that the flaps would need to extend nearly 90% of the foil span. This seemed like it would prove to be too complex for manufacturing. Our prototype design showed that the flap parts would be too small to withstand the expected loads. Full foil articulation seemed to provide for simpler manufacturing and a better accommodation of the expected loads (Figure 25).

Load transferring components

The load transfer components are divided between the foil and the pod. We began our designs with the articulation shaft and foil as a continuous piece of 6061

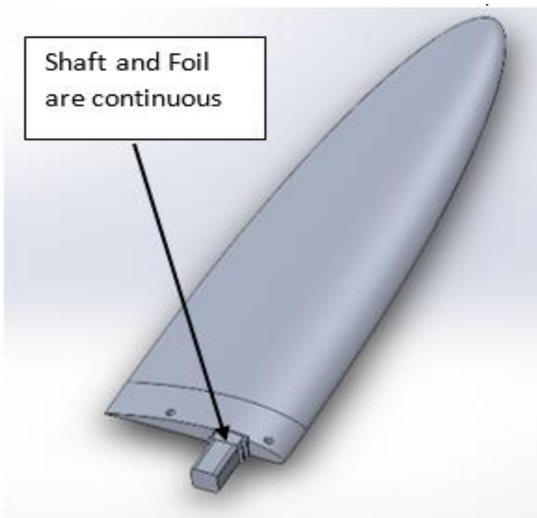

Figure 25: Half foil for articulation

Aluminum. (Figure 25).

As we developed the design, we realized, with 6061 Al, the diameter of the shaft could not be small enough while having an acceptable safety factor. Our industry partner, SeaLandAire, suggested we have a separate part to adapt the foil to the pod. The Foil-Pod adapter is made from 440C Stainless Steel and allowed us to have both a small diameter articulation shaft and acceptable safety factor.

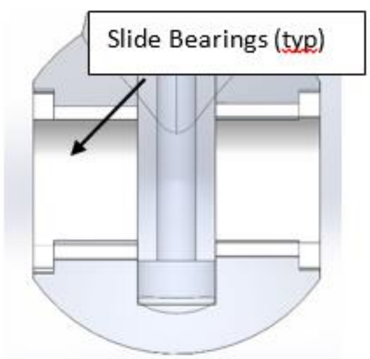

Figure 26: A cross sectional view of the original hydrofoil/drive train pod showing the location for the slide bearing

From the Foil-Pod adapter, the load transfers into the pod. We chose slide bearings to carry the load into the pod (Figure 26). But after an analysis of the bending moment from the lift, we decided that ball bearings would pass the load into the pod more effectively. With SeaLandAire's input, the final design incorporated three ball bearings for each foil and a load plate to help carry the load (Figure 27 and 28). It is difficult to know how exactly to analyze this loading situation. While being pulled between making large enough parts for the forces, and small enough parts for drag, we think this application of bearings and plate is the best design for our needs.

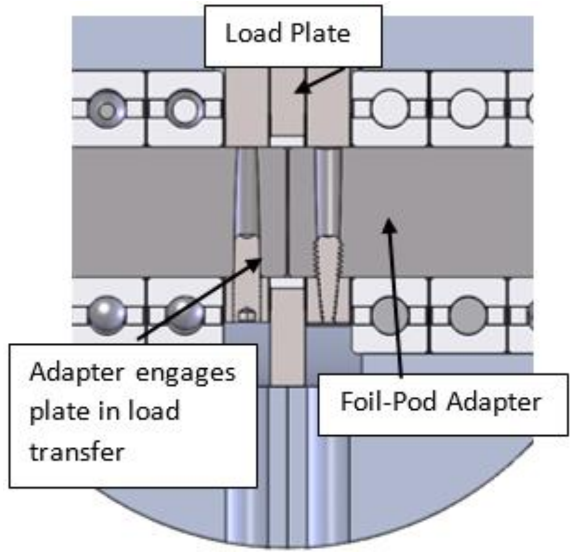

Figure 27: Annotated pod cross section

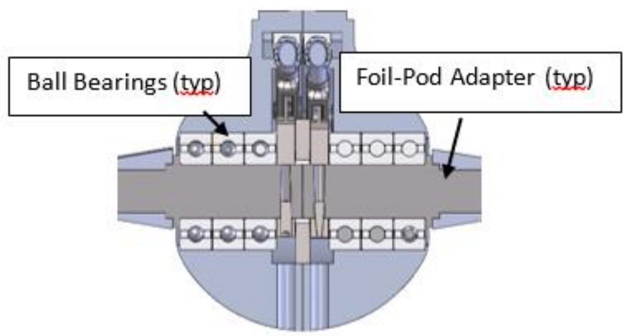

Figure 28: A cross sectional view of the pod showing the final design with ball bearings

Articulation component

Figure 28: Foil/ pod adapter

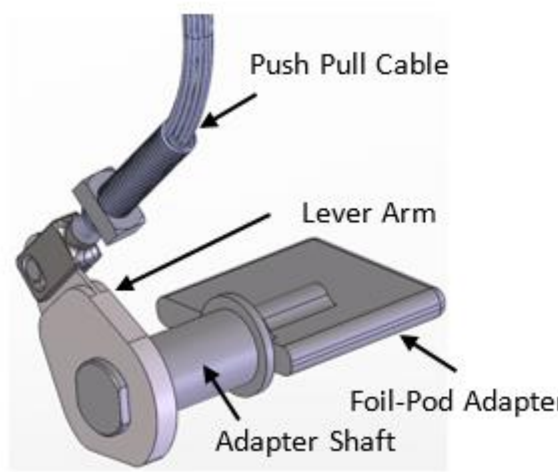

Figure 29: Articulation Mechanism

The purpose of the articulation components is to rotate the foils through the Angle of Attack (AOA) range. We had to overcome the torque about the adapter shaft created by the lift while remaining within the constraints of the actuator force, push-pull cable and lever arm length (Figure 29).

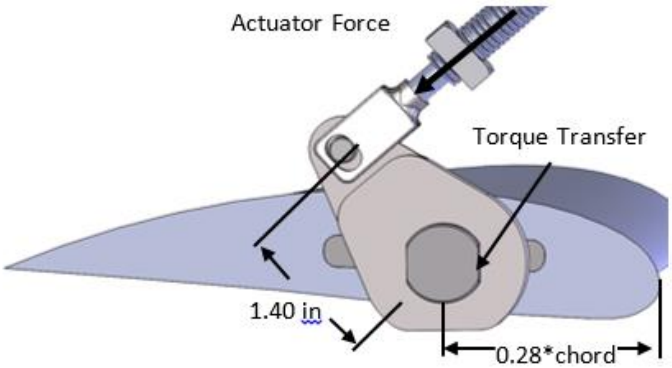

Figure 30: Dimensioned Foil Articulation

We placed the center of the adapter shaft at 0.28 chord from the leading edge of the foil (Figure 30). We analyzed the location of the lift through the AOA range and found the maximum torque about our shaft to be 55.12 in lb. We accommodated this torque with a combination of actuator force and lever arm length. Our actuator initially was capable of exerting 35 lb but we upgraded the actuator to 135 lb so that our lever arm length would not be too long. The push pull cables are off the shelf products from Cable Craft. The cables are capable of pushing 80 lb and pulling 120 lb. We chose the lever arm length of 1.40" so that the maximum force carried through the cables will be 41.25 lb.

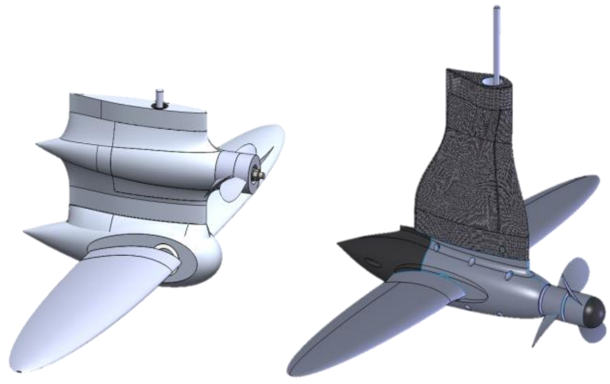
Figure 31: The transition in design from two pods (left) to one pod (right)

A portion of the designing process for the rear hydrofoil system was the interface and interaction with other systems throughout the boat specifically, the interaction with the drive train system. The first big concept we decided on was having a combined housing between the rear hydrofoil actuation and drive train systems. By doing so, this we were able to have the propeller mounted on the centerline of the hydrofoil. This provides even flow on the top and bottom of the hydrofoil. Secondly, we were able to reduce the drag of both systems if they had their own respective pods. Figure 31 above illustrates the change from two pods to one pod.

We also needed to consider how to make the pod shape more hydrodynamic. One way of doing so was the by creating an angle of decline of the rear piece of 15°. This 15° degrees was determined to keep attached flow and was found using available research reports that used similar Reynolds numbers and velocities to our parameters. The rear piece (Figure 31) also was made using laser sintering technology. This allowed us to reduce the weight of this piece, and can be sanded so that it does not affect our drag.

A second concept we needed to consider was the complexity of manufacturing and assembling. We wanted to make both processes as concise as possible, so we created a split housing design. For manufacturing a split housing design allowed for us to complete the entire interior on one face. If it were to be a solid piece, we would have to turn the stock multiple times and dealing with compounding tolerance errors. This is important, especially in the drive train system because of the efficiency we need to withstand. This is illustrated below in Figure 32.

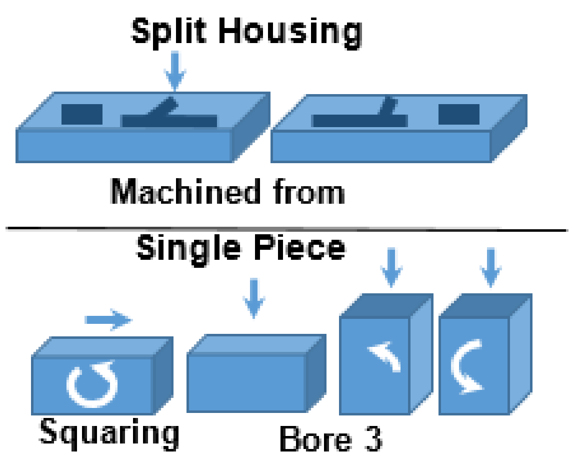

Figure 32: Manufacturing process for split vs. solid housing.

For assembling, we have access to both systems simultaneously when we take the split housing apart, which opens up room to complete any maintenance in a race scenario. The disadvantage is that leaking into the system is a greater concern. By adding sealed bearings, seals and a gasket around the drive train system, we hope to prevent this.

Creating a mechanical system to control roll while in flight was essential to the operation of the hydrofoils. Incorporating this system into the same pod as the drive drain introduced more design challenges, but proved to reduce pod drag and simplify assembly.

HYDROFOIL AND STRUT INSERT MANUFACTURING

In order to machine other complex parts, such as propellers, we used a Hurco CNC mill. Using toolpaths generated by CAMWorks We would machine the top half of the part in addition to two precision pin holes that would allow us to have an exact point to set the XY origin for the last half. However, manufacturing the hydrofoils presented us with a new manufacturing challenged to overcome; machining the end of the foil so that it could attach to the strut and pod which required machining on a third face.

In order to address this problem we sought a method of machining the pod side and then locating the part once it was rotated. Figure 33 below depicts the CAMWorks simulated view of the solution we reached. Using a precision "L" block to stand the stock vertically inside the mill, we were able to accurately machine the pod side.

However, as this side was the best place to leave a place to clamp the blade, we left two tabs to suspend the part once it was flipped. In order to locate the part once it had been rotated, we used a ball end of equal diameter to the precision pins to cut slots one diameter deep in these clamp tabs. Like the precision pins for a 180° rotation, these slots left an area for the part to be precisely located. By cutting one diameter deep, it allowed us to use a precision block to make sure that the remaining stock was aligned exactly with the x axis as the edge of the pin was flush with the flat of the tab.

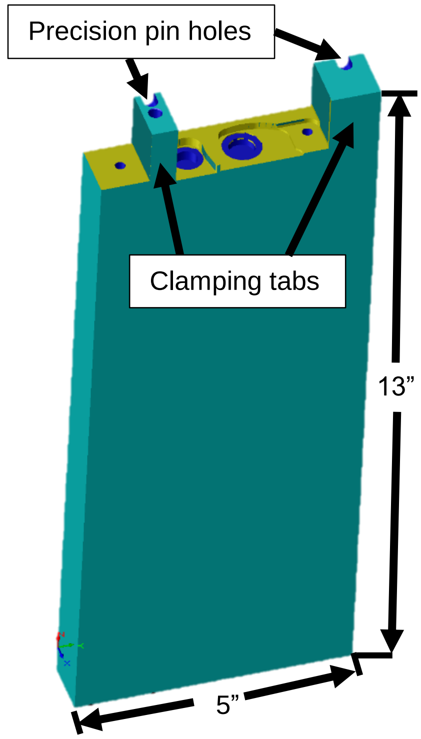

Figure 33: The stock standing vertically with the pod side milled out.

Accurately machining the blade also posed a problem as the length of the blade meant that vibration would be a significant problem if the blade was left cantilevered. In order to minimize this error we machined the top of the foil only as deep as was necessary to reach everything inaccessible from the other side as shown in Figure 34.

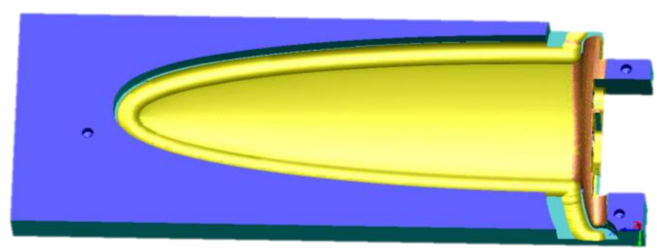

Figure 34: Top half of the blade milled

In order to finish the blade, we flipped it and located it using the pins as usual. After performing an area clearance to get rid of the bulk of material, we constrained to precision pass to move from the tip of the blade towards the clamps as shown in Figure 35. This meant that the blade itself was constantly supported right at the tool so that the cantilever distance was always zero.

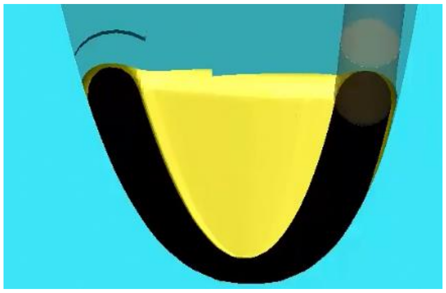

Figure 35: The support being removed from the tip

This support virtually eliminated any damage due to vibration in what would have been an excessive cantilever. By the end of this operation, the entire front foil and pod had been machined as needed with the exception of the tabs. The final operation performed by the mill was to cut slots in the tabs so that there would be a clear guide to finish the flat end with a band saw. The finished project is shown below in Figure 36.

Figure 36: A finished foil

STRUTS AND STRUT MOUNTING

The hydrofoil and drivetrain systems attach to the boat hull by means of supporting struts and internal mounts. These struts and mounts were designed to withstand the forces expected during typical racing conditions. Given our target speed of 36 km/hr and the approximate boat weight of 250 kg, these forces were determined and our design parameters set. Forces included in these constraints are the drag caused by the pod, strut, and hydrofoils in addition to the thrust produced by the drive train, the weight of the boat while flying, and the dynamic loading the will occur as a result of different pitch angles and turning on foils.

Strut mounts and struts must compose a rigid body that allows for force transition between the hydrofoil system and the boat hull. In addition, the mounts must allow for the struts to rotate about a vertical axis with the purpose of steering the craft. These mounts within the boat must also weigh at maximum of 4.5 kg.

Several options were explored and designs that included break-away systems in case of obstacle strikes were considered. Originally, the aft strut mount design incorporated the capability to rotate the strut about a horizontal axis to achieve efficient lift to drag ratios in various racing conditions. However, significant changes were made to this approach when the design for foil articulation changed. This rotation about a horizontal axis was also desirable because it would eventually lead to an avenue for a break-away design.

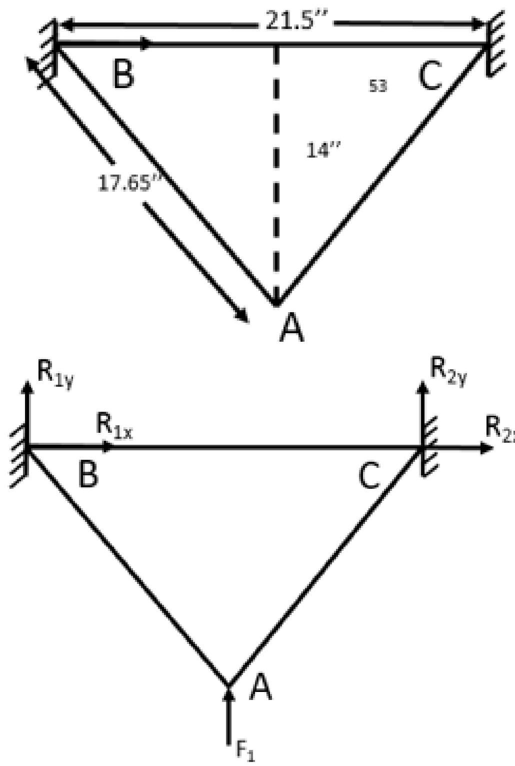

Figure 37: Free body diagram of loading scenario on rear strut mount

For the static lift case, free body diagrams were developed and structural analysis was completed to find approximate loads in supporting truss members. The free body diagram of this truss system is depicted in Figure 37.

The truss system would be used to support a cylinder with a rotating aluminum insert that would clamp to the strut. With a design like this, issues were brought up concerning the forces that would prevent the inserts from being able to rotate within the outer housing. Low friction material was considered to help with this gliding interface.

This design was hard to keep within the weight budget of 4 kg due to the size of the mounting pieces and it seemed difficult to confirm details concerning capturing the strut and holding everything in place.

As a result, an idea of using a bicycle steering mechanism was explored. Mountain bike headsets would be mounted inside a head tube. Specifically, large (56 mm diameter) mountain bike headsets seemed like a good option for our case because of the continual and extreme loading cases they experience over a lifetime of use. This design also offers consistent performance of the sealed tapered roller bearings inside. The bearings provide us with a solution to being able to easily turn the strut assembly and capturing of the strut steering tube is much like that of a bike. Figure 38 shows this assembly and its components.

This whole assembly will then be captured by an aluminum plate with a shoulder adapted to the head tube outer diameter. In addition, a Coosa board mount will be made as the structural member that will transfer the forces from the head tube to the hull. This assembly can be seen in Figure 39.

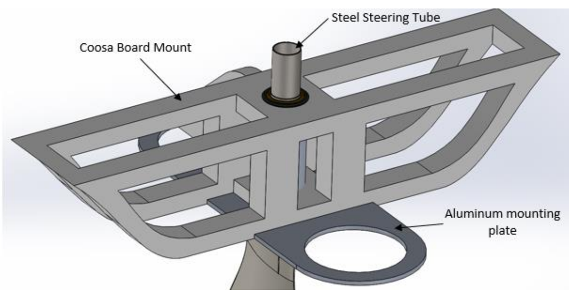

Figure 39: Coosa board and mounting plate on inside of the hull

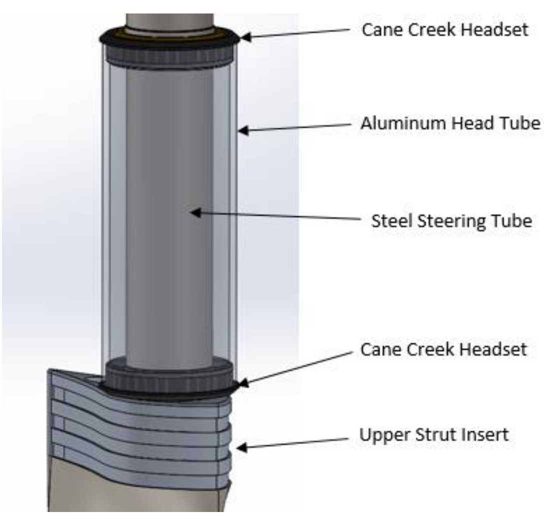

Figure 38: Strut Mount Assembly with headsets and steering tube mounted into the head tube

The finished design for the mounting heavily influenced our manufacturing and design of the strut. Much like a bicycle, our design uses a steering tube that passes through the head tube and is shrink fit into the upper aluminum insert in the strut shown in Figure 40. A similar aluminum insert is used to connect the strut to the pod. The strut shape is made from foam halves machined on the CNC router and then glued together. Channels are cut out of one side for the drive shaft and actuation cables. The whole assembly will then be put together and carbon fiber sleeves will be vacuum infused over the foam shape and over the grooved portions of the aluminum strut inserts.

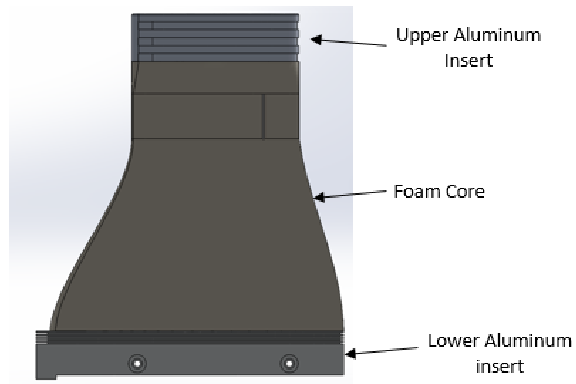

Figure 40. Strut Assembly

CONCLUSION

After performing studies in Xfoil and receiving a recommendation from the partner to Cedarville University's Solar Boat team, SeaLandAire, the profile was chosen to be the MH115. Upon choosing this profile, the planform was optimized as an ellipse to lift the boat weight of 550 lb and maintain a sufficient safety factor in bending. The drag of the foils were determined through the use of AVL and Xfoil.

The preceding process was encapsulated in the Matlab code, HydrofoilFlight.m. This code also accounts for stability through the use of AVL. While viewing this it was necessary to reduce the front foil size by 25% (5% of the weight of the boat) in order to come to a sufficient stability margin. This code also allows for 3D plotting of the boats stability, drag, lift and strength under different yaw, roll, pitch and speed conditions.

The front foil assembly was designed in order to reduce the travel of the center of pressure. This was accomplished by placing the point of rotation in the same plane as the hydrofoils and 25%. Placing the center of pressure at that location also allowed for the pull rod to in tension over the operating angle of attack range.

The rear hydrofoil articulation system and drive train are located within the same pod in two separate chambers. This combination allows for a reduction in drag and weight. The chamber had sufficient room for a lever arm to reduce the force in the push/pull cable. The split housing manufacturing of the drive train/ rear foil pod allowed for simpler manufacturing and assembly.

Using a Hurco CNC mill and CAMWorks allowed for the manufacturing of the front foils. In order to lessen the cantilever of the foil as the machining was occurring, the foil was machined in the chord direction, from span tip to root chord, slowly removing the edge material.

A bicycle steering mechanism was implemented in order to allow rotation about the vertical axis. This, implemented with a carbon fiber and a coosa board mount are expected to transfer the load to the hull.

All of these design decisions were made with the goal of racing the canard hydrofoil solar boat in the Dutch Solar Challenge at a cruising velocity of 36 km/hr (22 mph).

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Elijah Thompson is a senior mechanical engineering student at Cedarville University. He is responsible for the hydrofoil design, hydrofoil system drag analysis using Xfoil and AVL, and front foil assembly design for the 2016 Cedarville University Solar Boat Team. He will go on to work for JR Automation as a Mechanical Design Engineer.

Caleb Jacobson is a senior mechanical engineering student at Cedarville University. He is responsible for the system stability and maneuverability for the 2016 Cedarville University Solar Boat Team. He will go on to work for NatureScape as a R&D Specialist and will be pursuing a Master Degree in strategic leadership from

North Central University alongside a bachelors in studio production.

John Hopkins is a senior mechanical engineering student at Cedarville University. He is responsible for the rear foil articulation and is teaming up with Kevin Harmon on the integration of the rear hydrofoils and drive train pod. He will go on to work for Lockheed Martin as a Mechanical Engineer in mobile radar systems.

Kevin Harmon is a senior mechanical engineering student at Cedarville University. He is responsible for the designing of the lower gear unit of the drive train system for the 2016 Cedarville University Solar Boat team. He will go on to work for Motion Controls Robotics Inc. as a Mechanical Design Engineer.

Caleb Tanner is a senior mechanical engineering student at Cedarville University. He is responsible for the manufacturing of propellers, strut inserts, front hydrofoils, and general manufacturing.

Kyle Mary is a senior mechanical engineering student at Cedarville University. He is responsible for the strut manufacturing, transfer of loads to the hull, and the rotation of the front and rear strut. He will go on to work for A&P technologies as a Machine Design Engineer.