Design and Build of a Hydrofoil Boat

by

Nathan L. Basinger

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

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ABSTRACT

To investigate techniques of personal watercraft design and manufacturing, while exploring the functional use of hydrofoils, a small hydrofoil watercraft was designed and built.

The hull of the boat is a skiff measuring 14 feet and 5 inches in length and weighing 142 pounds. This hull was designed and built as a platform to support the development of the hydrofoil attachments. The watercraft is powered using a 15-horsepower outboard motor, an Evinrude Super Fastwin 1953, restored for the purpose of this project. Two surface-piercing dihedral hydrofoils were affixed to the hull to provide lift sufficient to raise the main hull out of the water. The dihedral surface piercing foils also provide the height control and roll stability necessary for stable flight. The hydrofoils are removable and thus allow the watercraft to be operated as a conventional personal watercraft when foiling is undesired. Estimates based on the hydrofoil boat design and manufactured components predict a takeoff velocity of 5 knots, with foils at a 6° angle of attack, a flying weight of 566 pounds, and a drag at takeoff of 283 pounds.

Thesis Supervisor: John Brisson
Tile: Professor of Mechanical Engineering

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1. Introduction

1.1 Naming Conventions

Prior to technical writing, there is significant vocabulary and nomenclature involved in both boating and hydrofoils. A hydrofoil refers to a wing placed underwater to provide lift. In this work “hydrofoil” may also to refer to a hydrofoil boat, the whole vessel that is equipped with hydrofoils. The word “foil” may also be used to describe the hydrofoil wing but will not be used to describe the vessel.

When discussing the structure of the boat, there are numerous naming conventions that improve clarity. The bow refers to the front of a boat and the stern refers to the rear. The fore refers to the front half while the aft refers to the back half, both in a more general sense. The transom is the end at the stern of the boat. The port side is the left side when looking towards the bow from the stern and the starboard side is the right from the same perspective. The gunwale is the top edge along the side of the boat. The keel is the structure that runs along the center of the bottom of the boat. Figure 1-1[1] is borrowed from the Poughkeepsie Yacht Club and illustrates most components described above.

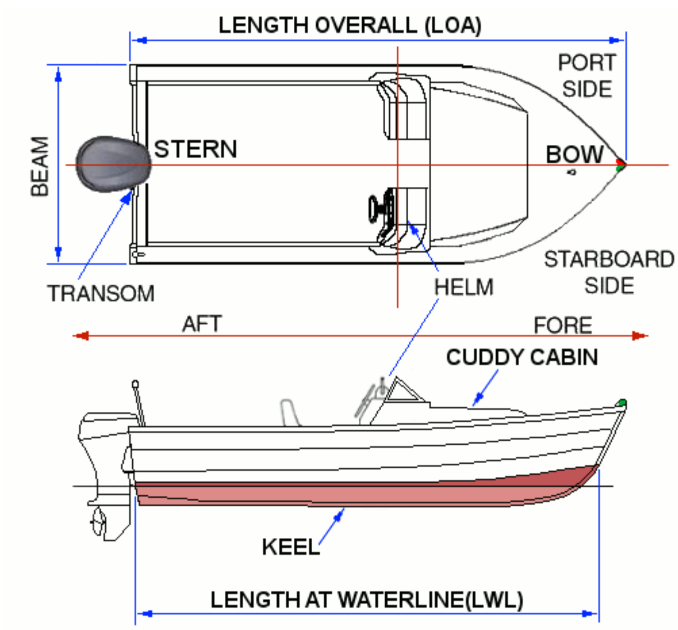

Figure 1-1: This illustrates the major components of the structure of a boat hull that will be used within this writing and are common in naval settings.

1.2 Governing Equations

When operating a conventional watercraft, there are two major regimes of operation, displacement and planing. In the displacement regime, the weight of the boat is supported by buoyant force. This buoyant force is equal to the weight of the volume of water displaced by the hull, hence the nomenclature. The top speed of a displacement hull can be approximated with Equation 1 below, where V_{Hull} is the hull speed [knots] and L_W is the length of the waterline [ft]. However, well-shaped hulls can exceed this estimation.

$$V_{Hull} \cong 1.34 \sqrt{L_W} \tag{1}$$

With a specifically shaped planing hull, once a watercraft is moving there is a dynamic lift provided by the hull. This lift provided by the hull reduces the volume of the hull in the water and thereby reduces the buoyant force. Once more than half of the weight of the vessel is supported by the lift provided by the hull, the vessel is said to be planing. While a watercraft is planing, the drag is reduced because less of the hull is in the water. With the drag reduced, a planing vessel can travel at a higher velocity than it can when displacing and so with more efficiency.

A possible next step of reducing drag, increasing efficiency, and increasing velocity for watercraft is the introduction of a hydrofoil. A hydrofoil is a wing that operates underwater to provide lift in the same way as that of an airplane wing. With hydrofoils attached under a watercraft, as the velocity of the vessel increases, the lift provided by the hydrofoils increases. This continues until the lift overcomes the weight of the boat and the hull comes out of the water.

In his book *Hydrofoils Design Build Fly*, Ray Vellinga describes the governing forces surrounding the use of hydrofoils [7]. To start, the formula for lift is seen in Equation 2 below, where L is the lift provided by the foil [pounds], ρ is the density of the fluid surrounding the foil [slugs], V is the velocity [ft/sec], S is the surface area vertical projection of the foil [ft^2], and C_L is the coefficient of lift [-].

$$L = \frac{1}{2}\rho * V^2 * S * C_L \tag{2}$$

As seen in Equation 2, lift increases linearly with surface area and coefficient of lift, but as the square of the velocity. This lift equation will later be used to calculate the necessary surface area for the foil and the takeoff speed for the hydrofoil boat.

The next governing force to consider is drag. The drag can be broken into two components the parasitic drag and the induced drag. The induced drag is drag created as a product of producing lift, while the parasitic drag is all other drag. The parasitic drag is given by Equation 3 below where D is the parasite drag on the foil [pounds], ρ is the density of the fluid surrounding the foil [slugs], V is the velocity [ft/sec], S is the surface area vertical projection of the foil [ft^2], and C_L is the coefficient of drag [-].

$$D = \frac{1}{2}\rho * V^2 * S * C_D \quad (3)$$

Equation 3 can also be used to calculate the total drag of a system by calculating the drag of each component of a system and summing them.

The formula for induced drag coefficient is given by Equation 4, sourced from NASA [8]. In Equation 4 C_{di} is the induced drag coefficient [-], C_L is the coefficient of lift [-], AR is the aspect ratio given by the span squared divided by the area, and e is an efficiency factor.

$$C_{di} = \frac{C_L^2}{\pi * AR * e} \quad (4)$$

In this equation, C_L will decrease with the square of the velocity as boat speeds up which means the parasite drag, not the induced drag, will be the limiting factor for the maximum speed of the boat.

2. Hull Manufacturing

Before attempting to attach foils to a hull and fly, a hull had to be constructed. The design for this hull was adapted from plans for a 12' skiff from Hannu Vartiala, an amateur boat builder, on his website *https://hvartial.kapsi.fi/* [2]. This design provided the basis for construction, but extra ribbing, runners, and support material were added.

2.1 Side Pieces

The first step in manufacturing the boat hull is transferring the profile of the side pieces to 3/8" plywood. These profiles can be seen in Figure 2-1.

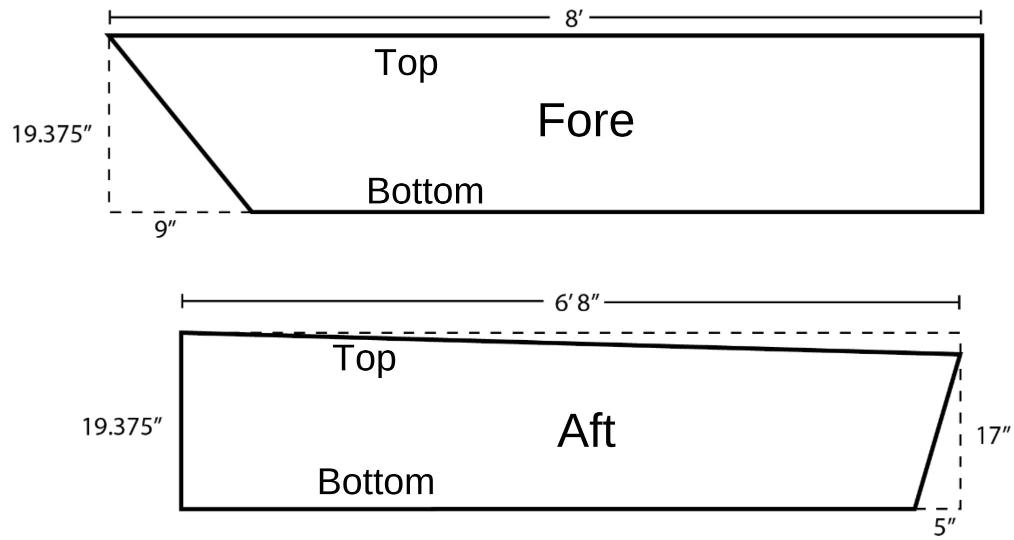

Figure 2-1: This shows the profiles and dimensions of the fore and aft sections of each side of the boat that must be joined to construct a side. The total length of a constructed side will be 14'8" with a height of 19.375" at the bow narrowing to 17" in the aft.

Since plywood comes in 4'x8' sheets, the sides must be constructed by attaching 2 pieces together after they are cut to shape. The dimensions for each side piece were marked with a pencil and connect with a straight edge. These profiles were cut out using a circular saw to yield 4 pieces of wood that will be combined to construct 2 side pieces. This attachment is done with a series of epoxy and fiberglass coatings secured by smaller sections of plywood. All epoxy used for the remainder of this writing are Pro Marine 521 Pro Grade Marine Epoxy using fast hardener and the fiberglass used is 9oz woven fiberglass cloth. First, the sections of plywood are prepared by aligning the sections to be joined and sanding all surfaces that will be adhered. Then, the sanded surfaces are cleared using a brush and compressed air to remove any remaining sawdust. Fiberglass cloth was cut to overlap each board by roughly 3 inches and overhang on the edges by a similar amount. Four of these fiberglass cloth sections were cut to make each joint. Two sections of plywood were also cut to the side of the joint, approximately 6 inches" by 19 inches, to provide a backing and additionally secure the joint. After these materials have been created, the process of attaching the board sections begins. The layering of this construction, during and after the epoxy curing, can be seen in Figure 2-2 below. A cup of epoxy is mixed, and the board section is wetted with epoxy. One layer of fiberglass cloth is laid on top of the joint and covered with epoxy. This section is smoothed with a plastic scraper to ensure excess epoxy is pushed out and that the fiberglass adheres to the wood. Then, the second piece of fiberglass is applied and epoxied on top of the first. Next, one of the plywood pieces is aligned on top of the fiberglass joint. This board is screwed down to ensure a tight connection. The entire joined piece is now flipped, and the process repeated for the other side. The only difference between the sides is that for what will be the outboard facing section of the boat, a layer of way paper is placed atop the final layer of fiberglass before securing the board to the joint. This will allow the board to be removed to give a smooth outer surface of the boat. With the sides jointed in the curing configuration, they were left to cure for approximately 24 hours.

With the joint fully cured, the exterior securing board was removed along with all screws. Then, matchsticks were dipped in epoxy and inserted through the screw holes to fill the holes. These matchsticks will be broken off later and sanded down to give a flush side, as through it was a single piece of wood.

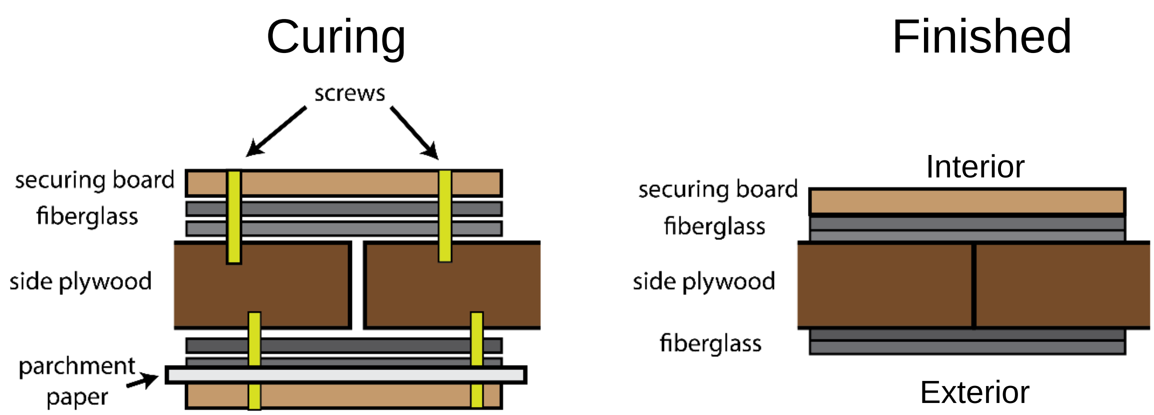

Figure 2-2: This figure shows the ordering of materials in the joints used to construct the sides of the boat. Notice the removal of screws in the exterior securing board in the finished state of the side pieces.

2.2 Bow

The stem, the most front support structure, was cut from a 30 inch section of 4x4 board, with actual dimensions 3.5”x3.5”. This bow piece will set the angle at the bow and be the mounting location for both side pieces. A band saw was used parallel to the length of the board to remove 1.5 inches of board, yielding a 3.5”x2” board of 30 inches length. Then, a straight edge fence was set up at a 1.5-inch offset from the center of this board as a guide to run a circular saw. Utilizing this guide, the board was cut at its center with a 60-degree angle. This procedure was repeated for the other half of the board to produce a 30-inch-long board shaped into an equilateral triangle with sides measuring 2 inches wide.

After the two pieces of the side are combined using the method described previously, the port side was attached to the bow piece. The bow end of this port side piece was lined up with the leading edge of the bow piece as a dry fit to ensure the dimensions appeared correct. Then, all contacting surfaces were sanded and dusted clean to ensure a suitable binding surface. These contacting surfaces were thoroughly covered with Titebond Type III wood glue and secured with 1.5” screws. For the remainder of this work, wood glue will refer to Titebond Type III wood glue.

At this point, the bottom of the bow piece was cut flush with the port side to aid in alignment of the starboard side. This step was a mistake as this cut resulted in a half inch triangular gap once the starboard side was attached. This is due to the sides attaching to the bow piece at angle which is not fully realized with only one side attached. However, his mistake will later be correct through use of a wedge glued into the gap but could have been altogether avoided with more throughout planning on the build procedures.

2.3 Transom

The next stage is making and attaching the transom. First, the transom was cut into a symmetrical trapezoid with bases of length 34.75 inches and 46.75 inches with an orthogonal distance of 17 inches. This shape can be seen in Figure 2-3 below. Two copies of this same profile were cut out of 3/8” plywood and then glued together and secured with screws. This produced a transom of .75” thick to ensure it would support the force of a 15 horse-power motor. The glue was allowed to dry for approximately 24 hours.

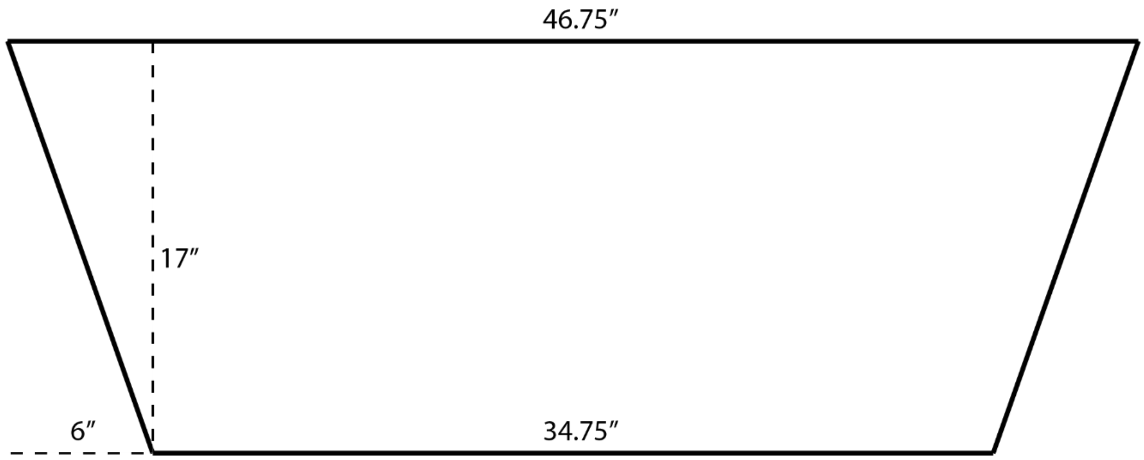

Figure 2-3: This shows the dimensions of the transom which was constructed using two layers of 3/8” plywood glued and screwed together. The screws were removed, and holes plugged before additional construction continued.

Once the glue was dry, all screws were removed, and the leftover holes were filled with matchsticks dipped in glue in the same process as the side pieces. The next step was to attach the sides to the transom. In this attachment, the transom was placed behind the end of the side pieces to prevent sheer on the interface. Using a pressure treated 2x2 boards along the interior of the joint, both the sides and transom were secured to these 2x2s with wood glue and screws. Once the glue was dry, the seams were filleted with a mixture of epoxy and sawdust that was mixed to the consistency of peanut butter and then allowed to cure fully

In the process of attaching the side pieces to the transom, a substantial discrepancy between the sides was noticed. At the transom, the port side was 19.375 inches when it should have been 17 inches. This was the result of an error made in transferring the side profile to the plywood. Rather than a narrowing profile caused by a downward slope on the top edge of the board, the port side was the same thickness throughout the side. With this error in mind, the transom was attached so that the bottom edges lined up correctly. Then, after the glue and fillet epoxy had cured, the error on the port side was corrected by trimming the port side to the correct dimension of 17 inches in height at the transom.

2.4 Ribs and Runners

The next stage of hull construction was to make and install structural ribs. Five ribs were used with roughly equal spacing. Using the measurements for the top distance, bottom distance, and side length, the angle necessary for ribs can be calculated using the inverse cosine of half of the difference between the top and bottom lengths divided by the side length. The resulting angle was used to cut the ribs which were then glued and secured with screws on each joint. As the glue dried, the edges of the ribs were sanded, and hand planned at an angle to fit the curvature of the hull more closely. The ribs were installed by preparing the side pieces by gently sanding the side contact area before gluing and clamping a rib in place, then screws were used to secure the rib in place. This process was repeated for each rib. After all ribs were attached, the corners where ribs meet the side of the hull were filleted with the same epoxy sawdust mixture mentioned earlier.

Along the bottom of the ribs, cutouts were made to install runners to distribute stress lengthwise along the boat. The cutouts were measured to be 12 inches apart centered symmetrically. These cutouts measured .75 inches wide by 1.5 inches vertically to tightly fit 1x2 board. These 1x2 boards were 10 feet long and thus needed to be lengthened to span the entire 13-foot hull floor. This was done though utilizing 1:8 angled scarf joints, which yields a 12-foot constant slope across the 1.5 inch wide board. This joint specification can be seen in Figure 2-4 below. These were constructed by using a hand plane to cut a constant angle, then glued and clamped together. These were left to dry for about 24 hours before being sanded smooth. Then, the runners were glued into the cutouts on the ribs and clamped at each rib.

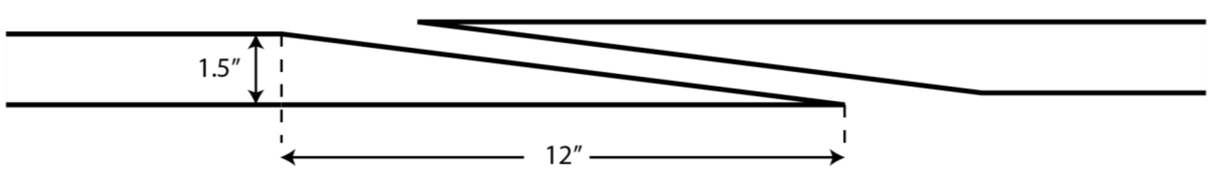

Figure 2-4: A scarf join 12” long across a 1.5” board yielding a slope of 1:8. This joint was used to extend the length of 1x2 boards from 10’ to 13’ to create runners along the inside bottom of the hull.

2.5 Bottom and Gunwales

With the runners attached and dried, the bottom of the hull was attached. A full 4x8 sheet of 3/8 inch plywood was aligned with the transom and an additional 5-foot section of plywood was aligned with the end of the previous piece to cover the entire bottom of the hull. Then, all contact points were sanded, brushed clean, and glued. The bottom pieces were then screwed to each rib to secure them to the rest of the hull. Once the glue was dry, all screws were removed, and the holes were filled with matchsticks in the same manner as the sides. At this stage, construction adhesive, Loctite PL Premium MAX, was applied to all the intersections of the bottom with another piece of wood. Although unnecessary, this adhesive was added to provide additional rigidity, remove slop, and ensure no gaps nor stress concentrations were created due to imprecision in previous gluing steps.

Once dry, a jigsaw was used to trim the excess wood. The intersection of the side and bottom pieces was marked by drilling a hole from the side through the bottom every 12 inches. These holes were then connected with a straight edge to provide a guide for trimming excess wood.

After the sides were cut flush, the gunwales were constructed and attached. Like the runners, the 1x2 board used for the gunwales needed to be extended to span the entire length of the gunwale. Again, a scarf joint was used with a slope period of 12 inches along the .75-inch profile of the board. This yields a slope of 1:16. This joint was made in the same process as the runners by cutting them with a hand plane before being glued and clamped in place. Once dried the gunwales were glued and secured to the sides with screws. Once dry, the screws were removed and plugged in the same manner as the sides and bottom.

2.6 Fiberglass Reinforcement

With the gunwales secured and dried, the hull was ready to fiberglass and epoxy. The corners were sanded to ensure a smooth transition for the fiberglass and prevent any sharp bends. Then, the entire waterside surface of the hull and sides were sanded with 100 grit sandpaper to allow for proper epoxy bonding. This surface was finally blown off with compressed air to remove any remaining sawdust.

Fiberglass was unrolled to and cut to yield two 12-foot sections to cover all but the most fore section of the hull and sides. These sections were overlaid with at minimum a 6-inch overlap and manually smoothed to the hull. Then, epoxy was mixed in batches of about one cup and spread over the fiberglass. Epoxy scrapers were used to ensure epoxy had fully penetrated the fiberglass to the wood. Once full coverage of an area was achieved, the section was scraped again with gentle pressure to remove and excess epoxy. This redistributed excess epoxy into areas with less coverage to lower the total amount of epoxy mixed as well as preventing clumping or pooling of excess epoxy. While the aft section was still uncured, additional fiberglass was cut to shape of the fore section of the hull. This was applied in the same manner as the aft section. One crucial detail was wrapping and overlapping at the corners of the transom and bow. At each edge, the fiberglass was cut in a straight line to the corner and the resultant flaps were wrapped around the edge. This gives the edges, the weak points of the vessel two layers of fiberglass reinforcement. However, this does leave a hole at the weakest point, the corner. To cover the holes left at each corner, small patches of fiberglass, approximately 5 inches by 5 inches, were used to cover the holes and cured in place with epoxy. All epoxy was left for about 36 hours until fully cured. Once cured, the boat was flipped to expose the inside of the vessel. A thin layer of epoxy as spread over the entire inner surface to help prevent wear and provide slight weatherproofing for outdoor use. During this epoxying, strips of fiberglass were placed at the transitions from the floor to the sides to provide added strength and an extra layer of waterproofing should the outer layer have defects or become compromised.

2.7 Finishing Elements

With the boat fully glassed, a wooden breasthook and corner bocks were added to distribute force at the seams of the vessel. These were attached with construction adhesive and clamped in place until dried enough to support their own weight, approximately 1 hour.

The next element added to the hull was a water barrier termed the “false transom”. The water intake for the engine is about 16 inches below the top of the transom mounting location. So, to provide propulsion and allow the engine to cool itself when foiling at a height of 10 inches, the transom must be cut to 6 inches above the bottom of the boat. This does not afford enough height to survive even meager waves, so the false transom was added to collect and expel any water that might come over the transom. This false transom cut using measurements of the hull parallel to the transom but 10 inches offset towards the bow. Cutouts were made to accommodate the runners and the false transom was tightly fit in place. It was then secured with peanut butter, the epoxy and sawdust mixture.

With the false transom installed, it was time to construct and attach a keel. The keel was made from a 1x3 board. The board was ripped in half to yield two boards measuring .75” by 1.25”. These boards were affixed end to end with a scarf join in the same manner previously described with the runners. Once dried and sanded to be a continuous board, the keel piece was affixed to the bottom of the hull along the center using wood glue and 1.5” screws. Before gluing, the epoxy along the contact area was sanded to provide a surface suitable for gluing.

3 Foil Design

3.1 Configuration

With the hull constructed it was time to design the actual hydrofoils and find a way to attach them to the hull. When designing the foils, there are many options and theories for the overall design of the system. For this project, a canard configuration was selected. In the canard configuration, there is a large rear foil to the aft of the hull with a smaller foil in the fore. The larger foil supplies most of the lift and handles roll control, while the smaller foil provides some lift but also acts to control the pitch of the hull. This configuration tends to be the most common and is generally recommended for outboard motor-powered hydrofoils. The canard configuration also makes sense with the manufactured hull because the motor and rider will be positioned toward the aft of the boat, making the center of gravity (CG) closer to this foil.

3.2 Hydrofoil Profile Selection

With the canard configuration chosen, the next step was determining a hydrofoil profile. This is the shape of the foil looking perpendicularly from the side of its motion.

Choosing a foil profile can be complex and tedious, without an objective “best” profile. Profiles can vary by overall shape, thickness, concavity, and other factors all of which contribute to flight characteristics. These designs and factors are outside the scope of this writing and require significant investigation. Rather than undertaking this investigation, foils were selected for their ease of manufacturing and history of prior use, while keeping in mind the performance necessary to fly. The National Advisory Committee of Aeronautics (NACA) has extensively published and researched may foil profiles, making profile selection from existing profiles an easier option. The first profile selected for this hydrofoil boat is the NACA-4412, seen in Figure 3-1 below.

This profile is one of the most prevalent hydrofoil shapes and is relatively easy to manufacture as its bottom is mostly flat and has no concavity. The plots for the coefficient of lift, coefficient of drag, and lift per drag across attach angles (alpha) for this foil are shown below in Figure 3-2, labeled a, b, and c respectively.

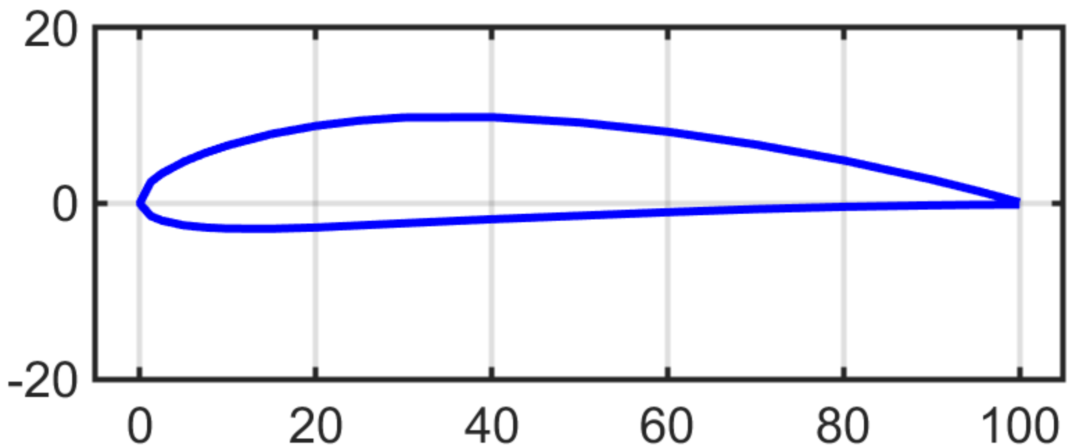

Figure 3-1: This shows the profile of a NACA-4412 cross section.

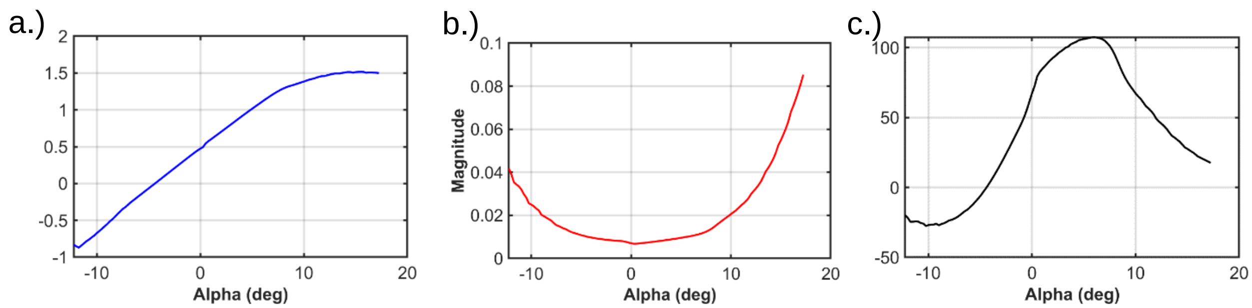

Figure 3-2: For a NACA-4412 hydrofoil profile these plots show the lift coefficient, drag coefficient, and lift to drag ratios in a, b, and c, respectively. These plots are at a fixed Reynolds number of 500,000. The maximum lift per drag is seen to be 107.5 at α=6°, which corresponds to the most efficient attack angle for this hydrofoil profile.

The above NACA-4412 profile was used for the larger rear foil of the boat. This profile conveniently fits the dimensions of a 2x10 board which aided in its construction. For the smaller front foil, the same profile was planned. However, upon seeing the thickness of the profile scribed upon a 2x6 board, it was apparent that a larger cross section would be more efficient to manufacture and produce less waste wood. After investigation the NACA-4418 profile was chosen at it has nearly the same profile, as seen in Figure 3-3 below, but at a thickness 18% of the cord length rather than the 12% afforded by the NACA-4412.

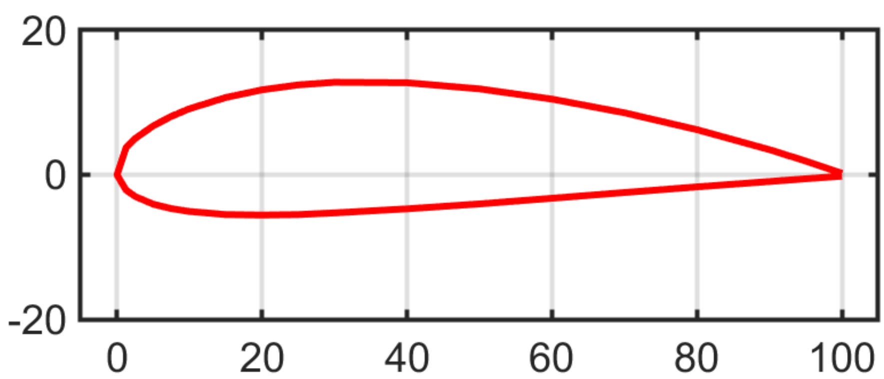

Figure 3-3: This shows the profile of a NACA-4418 cross section.

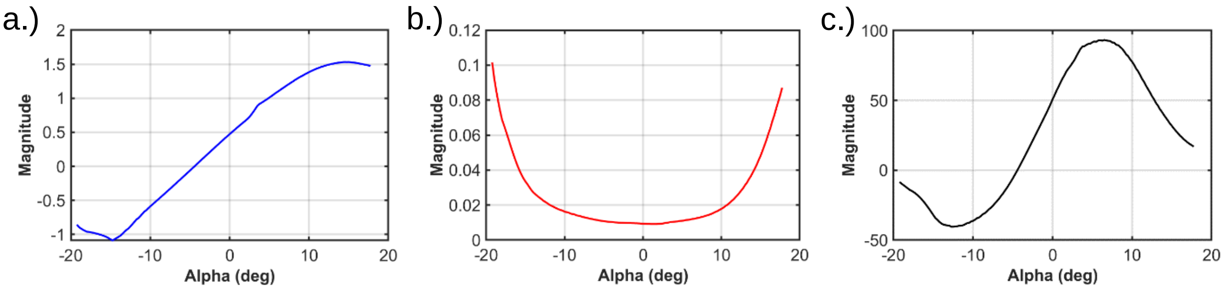

Figure 3-4: These plots show the lift coefficient, drag coefficient, and lift to drag ratios of a NACA-4418 hydrofoil in a, b, and c, respectively. These plots are at a fixed Reynolds number of 500,000. The maximum lift per drag is seen to be 93.29 at α=6.5°, which is slightly less efficient and at a slightly higher attack angle compared to Figure 3-2.

The added thickness of this foil also serves to slightly increase the strength and rigidity of the front foil. The plots for the coefficient of lift, coefficient of drag, and lift per drag across attach angles (alpha) for this NACA-4418 foil are seen above in Figure 3-4. These are labeled a, b, and c respectively and are very similar to the NACA-4412 curves in Figure 3-2.

The section needing to be shaped as a symmetric foil were the struts used to support the other hydrofoils and attach them to the hull. While these strut sections are not intended to provide lift, shaping them into a NACA-0012 foil reduces the drag coefficient as the C_D for a rectangular rod (approximation of a board) is about 2. The cross section and drag profiles for a NACA-0012 foil can be seen in Figure 3-5 below.

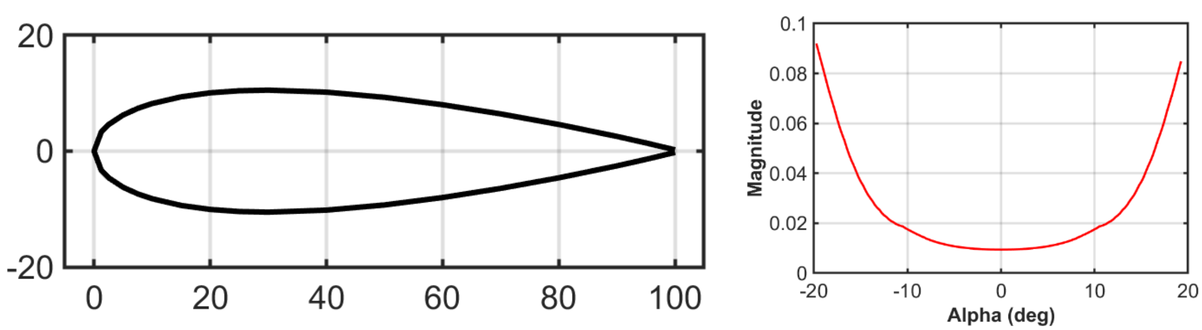

Figure 3-5: This shows the profile of a NACA-0021 foil along with its corresponding drag coefficient plot at a fixed Reynolds number of 500,000. The minimum drag coefficient for this profile is ~0.01 which is 2 orders of magnitude smaller than an unshaped board would have afforded.

3.3 Height and Roll Stability

There are several methods to control both the flying height and rolling of a hydrofoil watercraft. The height can be controlled using a surface follower, a depth sensing mechanism, or using surface piercing foils among other options. For mechanical and manufacturing simplicity, surface piercing foils were chosen as the mechanism of height control. When operating, surface piercing foils extend through the surface of the water. The variable wetted area of the foil translates to a varying effective surface area for the foil, and thus changes in lift. As the foil sinks in the water, more of the structure acts as a foil and provides lift. Then, as the foil raises in the water more of the foil leaves the fluid and reduces the lift. These changes are used to reach an equilibrium height which is known as the cruising height.

Roll management, like height management, can be done in several ways. More precise methods include wing warp or using flaps and ailerons. However, there is an option to use dihedrals, which will pair well with a surface piercing foil. With a dihedral wing, the wingtip is higher than the base of the wing. This angling of the wing means the lift provided by the wing comes at an angle, which produces a moment on the hull. The direction of this moment is the result of force vector from the dihedral. If the force from the dihedral is direct above the center of gravity, the dihedral provides a moment rolling the boat away from the foil. This is desirable for roll stability in a surface piercing hydrofoil. In the case of surface piercing dihedrals, when roll is directed toward a dihedral, more of the wing is in the water and can act as foil. This increases the lift and works against the roll to level the watercraft effect of dihedral wings is visualized in Figure 3-6.

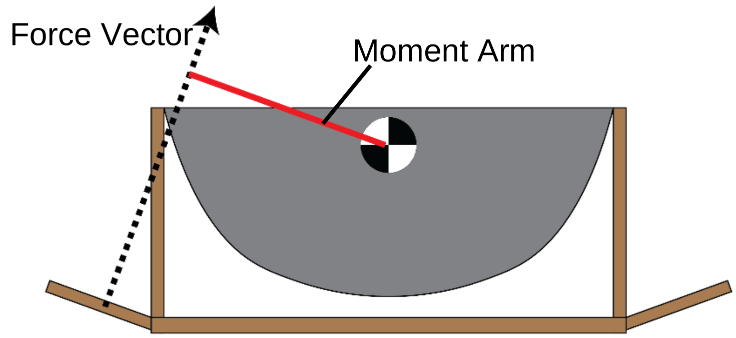

Figure 3-6: This shows the force vector provide by the dihedral and the moment arm about the center of gravity

For this hydrofoil boat design, the struts were placed outside of the hull as shown above in Figure 3-6. This positioned the rear struts 42 inches apart and the front struts 33 inches apart.

3.4 Lift Calculations

For a hydrofoil boat to raise its hull from the water and truly fly, the lift provided by the foils must overcome the weight of the boat and its cargo. For this project, the hull was measured to weigh 150 pounds, the outboard engine with gas weights up to 100 pounds, the rider weighs 250 pounds, 46 pounds for the foils, and there is about 20 pounds of additional safety gear such as oar, extra life jackets, and seating. This makes the total weigh to overcome about 566 pounds. Looking at the above foil designs, 6 degrees will be the chosen cruising angle of attach to maximize efficiency. This yields an approximate coefficient of lift of 1 when rounded down. Although the foils are of a slightly different profile, the front and rear foils can be approximated to the same coefficient of lift. For a takeoff speed of about 9 feet per second, the surface area necessary for the foils can be calculated using Equation 1.

$$L = \frac{1}{2}\rho * V^2 * S * C_L$$

$$520 = 9^2 * S$$

$$S = 6.42\ ft^2$$

The result is an estimate that the foils need to have roughly 6.5 square feet of surface area combined.

With minimum surface area in mind, the foils were designed to extend slightly wider than the hull for their flat section. Then, the dihedrals were added and made long enough to pierce the water. Along with these considerations, standard lumber lengths of 96 inches with the goal of reducing waste helped to inform the foil lengths. Starting with the front foil, the chord length is 5.5 inches (the width of a 2x6 board) with a length of 39 inches. Converting to feet and calculating this surface area yields 1.48 square feet. Then the lift provided by the dihedrals must be accounted for. The two dihedrals have the same 5.5-inch chord length but with a length of 15.5 inches for a total surface area of 1.18 square feet. With the dihedrals angled at 40 degrees, the portion of lift provided vertically is given by sin(40°) = .6427 to give them the equivalence of .76 square feet of horizontal foil. Together, this gives the front foil 2.24 square feet of surface area.

Now, turning toward the rear foil with a chord length of 9.25 inches (the width of a 2x10 board) and a length of 47 inches, the horizontal foil surface area is 3.01 square feet. The rear dihedrals have the same angle as the front dihedrals, so the same fraction of 64.27% of their lift contributes to upward force. With their 10-inch chord and 23.5-inch length, the two rear dihedrals have a surface area of 3.02 square feet which relates to 1.94 square feet of horizontal foil surface area. This gives the rear foil 4.95 square feet of horizontal foil surface area.

With both foils combined, the total horizontal equivalent surface area is 7.96 square feet. We can now use Equation 2 to calculate the velocity where takeoff can be expected. The lift required will be 566 pounds, with a coefficient of lift rounded down to 1, and the surface area that was just calculated at 7.96 square feet. Rearranging Equation 2 results in the work below.

$$V = \sqrt{L/(S * C_L)}$$

$$V = \sqrt{566/(7.96 * 1)} = 8.36 \frac{ft}{s} \approx 5\ knots$$

This produces an expected takeoff velocity of 8.36 feet per second, which is slightly below the 9 feet per second estimate chosen before. This makes logical sense that the takeoff velocity is lower than the project because the surface area for the foils is larger than the minimum produced by that lift estimate, 7.96 square feet compared to 6.5 square feet.

3.5 Foil Placement

When deciding where to attach the foils there are several considerations but the primary concern was structure. For the foils to support the entirety of the boat, 520 pounds must be supported by four attachment points. These attachment points need to be selected to allow the forces coming from the foils and struts to be distributed across the hull rather than concentration and leading to damage. To aid in this force distribution, the attachment of the foils, through the struts, was done at ribbing locations. For pitch stability, a longer span between the foils is helpful, so the foils were placed just behind the first rib in the bow and behind the most aft rib. To attach the foils, hardpoints in the fore were added to the hull by shaping 4x4 blocks to fit the curve of the side then glued and screwed at the intersection of the rib and side. In the aft, a brace between the false transom and last rib was made with a vertical section of 2x4 and a horizontal section of 2x4. These were arranged in a T configuration before being glued and screwed to the hull and rear most rib.

With the locations of the of the foils mapped, estimates were made for the location of other weight additions to the boat, namely the pilot, motor, gas tank, and safety gear. The location of all weights was measured from the top edge of the transom, due to its convenience and accuracy as a measurement datum. These locations will be used to find the center of gravity and determine the lift required from each foil. Choosing placements that allow for ease of use and general intuition, the location and weight of components was estimated as follows in Table 3-1. This table follows the instruction of Vellinga's approach on page 192 in *Hydrofoils Design Build Fly* [7].

Component	Weight [lbs]	Distance from Stern [in]	Torque [in lbs]
Motor	80	0	0
Rear Foil	31	24	744
Rider	250	33	8250
Gas Tank	20	40	800
Hull CG	150	74	11100
Safety Gear	20	100	2000
Front Foil	15	128	1920
Totals	566		24814

Table 3-1: This shows the location and weigh of components in the hydrofoil boat and the torque those weights and locations apply. This will used to find the center of gravity and calculate the lift needed by each foil.

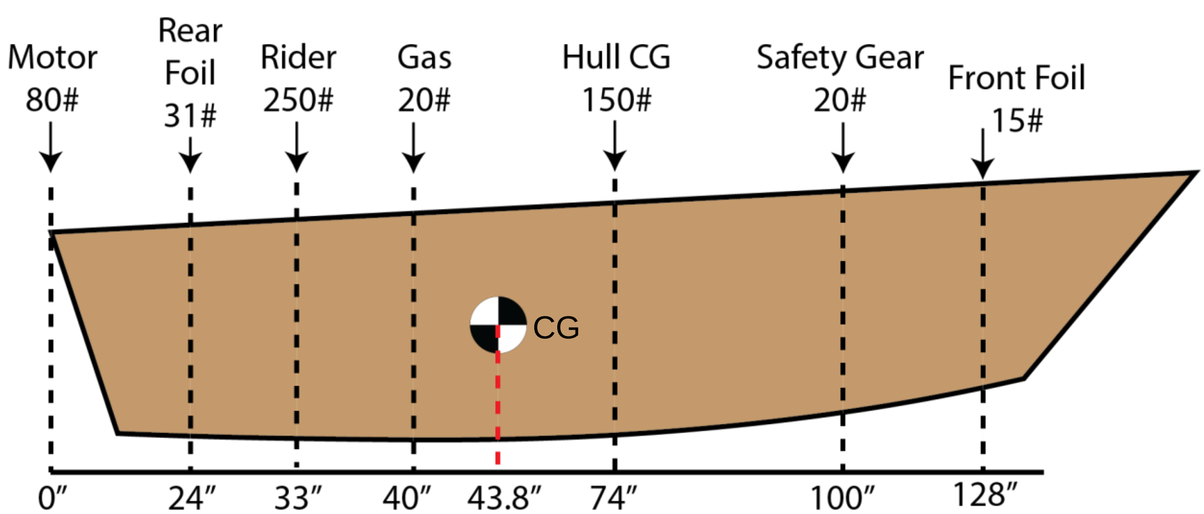

Figure 3-7: This shows the location and weigh of components in the hydrofoil boat. This was used center of gravity (noted on the figure) at 43.8 inches and calculate the portion of lift required by each foil.

The total center of gravity can be calculated by dividing the total torque calculated from Table 3-1 and dividing it by the total weight from the same table. This yields 24,814 inch -pounds divided by 566 pounds for a center of gravity located at 43.84 inches from the stern. With the center of gravity location, the distance from a foil location to the center of gravity, divided by the distance between foils will provide the portion of torque arm provided by that foil. For the rear foil at 24 inches from the stern, the distance to the CG is 19.8 inches. With the foil span being 104 inches, the real foil has 19% of the torque base. Looking at the front foil, it is 128 inches from the stern making it 84.2 inches from the CG. This yields 81% of the torque base utilized by the front foil. From these values, the portion of the weigh for each foil can be calculated by subtracting the percentage of torque base used by 100%. This calculation shows the rear foil will support 81% of the total weight and the front foil will support 19% of the total weight.

3.6 Power and Drag

A major factor in determining if a hydrofoil boat will fly is in the drag and power requirements. Without the necessary power to overcome the drag and reach a speed great enough to provide the lift necessary for flight. Recall Equation 2 which can be used to calculate the drag.

$$D = \frac{1}{2}\rho * V^2 * S * C_D$$

As before, one half times the density of water can be roughly approximated to 1 yielding the equation:

$$D = V^2 * S * C_D$$

This can be substituted into a power calculation to give the below equation for power where P is power, C_D is the drag coefficient and V is velocity.

$$P = C_D * S * V^3$$

Vellinga provides another formula here to convert to the typically used units in horsepower:

$$Hp = \frac{P * V}{33{,}000} = \frac{C_D * S * V^3}{33{,}000}$$

Using the above equations, the drag for each strut and foil can be calculated and added together to get an estimate of the drag. However, this method has large challenges and inaccuracies, particularly in estimating coefficients of drag. The exact profile of the manufactured foil along with any inaccuracy or defect can vary the drag coefficient by orders of magnitude. Along with those challenges are the interactions at joints such as where the foil transitions to a dihedral or the struts attach to the foils. These abrupt changes must be streamlined to prevent dramatically increasing the drag, but the effect of this streamlining is difficult to predict and out of the scope of this project.

Vellinga suggests a potentially more accurate and certainly quicker way is to use known lift to drag ratios to estimate the ratio for a given craft [7]. Then, the drag can be solved for since the lift must be equal to the weight of the craft, this is seen in Equation 5 below where D is drag, L is lift, and R is the lift to drag ratio.

$$D = \frac{L}{R} \tag{5}$$

Based on two previous hydrofoil boats, the Dynafoil and the Hifybe have lift to drag ratios of 2.9 and 3.5 respectively at takeoff. These foils have more precisely manufactured foils and more streamlined struts, so the estimation for this hydrofoil boat will be lower. I will use and estimated takeoff lift to drag ratio of 2. This should improve as the hull and struts leave the water and reduce drag, so I will estimate a maximum lift to drag ratio of 5 based on the Hifybe’s 7. The estimates and the 566-pound flying weight result in estimates of 283 pounds and 113.2 pounds for the drag at takeoff and maximum L/D respectively.

Another method for finding the drag is to tow the boat behind another boat with a scale attached to the tow rope. This would yield closest to the true drag since this is simply measuring the drag experimentally. The author was unable to source a spring scale and take measurements in time to get results in this paper, however this is an area of future exploration.

The final calculation in examining hydrofoil flight is finding the horsepower needed to power the boat. The formula used for this is seen in Equation 6 below.

$$P_{hp} = (D_{lbs} * V_{\frac{ft}{s}})/550 \tag{6}$$

In this equation, P_{hp} is the required delivered power, which can be estimated to be 50% of the nominal power of an engine, D is drag, and V is the velocity of the boat. Using this equation with the takeoff drag of 283 pounds at a takeoff velocity of 5 knots (8.36 ft/s), both values calculated earlier, the necessary P_{hp} to takeoff is 4.3 hp. This delivered power can be estimated to be 50% of the nominal power of an outboard engine. Thus, the 15 hp motor that was selected to power this hydrofoil boat is an appropriate choice.

4. Summary and Conclusion

This project set out to design and build a hydrofoil boat, from an engineering background, but limited direct experience. Using online plans for a 12-foot-long skiff, a similar yet original design was constructed for a 14-foot skiff with additional reinforcement and structure. In manufacturing the hull, the sides were constructed and attached to a bow piece. Then, the stern ends were attached to the transom. Ribbing was constructed and inserted into this form to give the hull its true shape. Then, runners were added lengthwise along the hull to aid in force spreading and dissipation. The bottom was added, and gunwales were secured to the sides. The entire hull was reinforced with fiberglass and epoxy and finally finish elements were added. This hull was measured at 14 feet, 5 inches in length with a maximum width of 54 inches. The hull weighs 142 pounds and center of gravity was found to be 74 inches from the stern.

With the hull built, focus turned to the hydrofoils. A canard configuration was used with a NACA-4412 profile on the larger rear foil and a NACA-4418 profile used for the smaller front foil. Each of these foils has a dihedral at 40° that is surface piercing. This allows the foils to provide height regulation and roll stability. The foils combine to provide approximately 8 square feet of surface area. The foils were attached to the hull at 24 inches and 128 inches from the stern for the rear and front foils respectively. This gives the foins a 104 inch span and with the intended flying configuration results in 81% of the weight being supported by the rear foil and 19% of the weight supported by the front foil. With the hydrofoils and their attachment to the hull, the entire vessel is calculated to have 283 pounds of drag at takeoff. The takeoff for this hydrofoil boat is calculated to occur at roughly 5 knots using an angle of attack of 6° and loaded in the flying configuration at 566 pounds. This takeoff is projected to require 4.3 hp at the propellor which will be provided by a 15 hp outboard engine, the Evinrude Super Fastwin 1953.

In physically testing, the boat was capable of flight and successfully foiled. Images of the craft foiling are shown below in Images 4-1 and 4-2. The craft began to fly at roughly 6 knots which required and estimated 7 hp at the propellor. The discrepancy between the calculated projections and physically observed takeoff velocity and power required are due to numerous sources. First, when fiberglass reinforcing the hydrofoils, the fiberglass separated on the trailing edge of the wing. This will reduce the lift provided by each foil. On top of imprecise foil manufacturing, there was a high degree of uncertainty in measuring and fixing the attack angles of the foils. This led to a slightly lower angle of attack for the rear foil which reduces lift, making flying more difficult. Finally, the most important factor for performance discrepancy is in creating drag. The side struts supporting the hydrofoil dihedrals and the struts themselves were not streamlined all the way to the waterline. This means sections of unshaped 2x4 and 2x6 are being drug through the water, dramatically increasing the drag and requiring more power to move the boat.

Image 4-1: This shows Ryan Nall flying the hydrofoil boat on the Charles River during testing.

Image 4-1: The author flying the hydrofoil boat on the Charles River.

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