Design and Construction of a Hydrofoil Watercraft

by

Ryan Nall

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

A design project aiming to construct an operational hydrofoil watercraft powered by an outboard engine. The hull of the vessel was constructed of plywood and timber, measuring 14' 6" long with a 54" beam. A 15-horsepower outboard engine was utilized as the vessel's power plant. The hydrofoils were arranged into surface piercing dihedral foils and utilized NACA 4412 and NACA 4418 foil cross sections. Documentation of the design and build process was maintained to help destigmatize hydrofoil technology and bring awareness of the benefits hydrofoils possess. Testing of the hydrofoil watercraft occurred on the Charles River.

The vessel's hull demonstrated remarkably accuracy between prediction of the numerically calculated maximum drag and speed values and the experimentally obtained results. The high degree of correlation between the vessel's hull and its calculated performance indicates a high degree of likelihood of success of the foils once attached to the vessel. Calculations estimate a takeoff velocity of 8.4 knots, requiring just less than 2/3 of the motors rated capacity. More data needs to be collected to adequately study other parameters surrounding hydrofoil technology.

Thesis Supervisor: John Brisson
Title: Professor of Mechanical Engineering

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Acknowledgments

I would like to thank Nathan Basinger for completing this thesis with me. Without his valuable input and contributions, a project of this scale could never have been realized

I would like to thank Professor John Brisson for serving as our thesis advisor. He dedicated many hours to helping us with project details, providing critical insights and bringing vast experience on the topic of boat construction. He helped point the project in the correct direction many times and ensured all major decisions were grounded in first principles of engineering.

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Introduction

Hydrofoils are lift generating wings placed on boats below the surface of the water that can generate enough lift to raise a boat's hull out of the water to reduce drag, increase fuel economy and increase top speed. Hydrofoils commonly have similar cross sections to airplane wings and function in similar manners. First designed and tested in the early 1900's by the Meacham brothers, hydrofoil research coincided with the rise of airplane attracting many inventors, including the Wright brothers, to develop early models.

Interest in the valuable benefits of hydrofoils has fluctuated over time. Hydrofoils were researched quite heavily in the 50's and 60's with the military funding many experimental vessels. In addition to higher top speeds, hydrofoils have the unique ability of maintaining steady deck without pitching or rolling action. Since the hull of a hydrofoil is not subject to buoyancy changes by waves in the water, the boat can remain stable aiding certain military operations. The US Navy produced six operational hydrofoils as part of the Pegasus class of vessels in the late 1970's. [1] These vessels were fast attack patrol boats and could reach speeds of 55 mph while airborne. In service from 1977-1993, these vessels saw great success with coastal monitoring missions but were retired due to cost and lack of use in an offensive mission orientated Navy. Hydrofoil technology has even been suggested for large container ships to take advantage of their increased fuel performance. Unfortunately, hydrofoil technology has had trouble maintaining traction in the military and civilian boating industries due to an uncertain need for the added complexities of a hydrofoil. Despite some challenges, hydrofoils are unique in their ability to both increase top speed and fuel efficiency without sacrificing performance of any other attributes. Recently hydrofoils have made a resurgence in popularity, being coupled with a surfboard for self-propelled or electrically power propulsion.

Increased access to hydrofoil construction plans and guidance is necessary to expanding the influence and beneficial impact of hydrofoil technology. Hydrofoils are currently limited to commercial manufacturers or dedicated innovators that perform much of the design and build work themselves. Hydrofoils are unique in that their full potential is yet, untapped. Unlike other technologies that have already been developed, hydrofoil technology and its application is still relatively untapped allowing sole inventors the ability to make great advances in this field. This thesis aims to improving ease of access of information relating to hydrofoils and their construction can help expose them to a wider audience and help develop a richer base of knowledge for inventors to build from.

A 14' 6" hull was constructed to test homemade hydrofoils and their performance. An outboard motor was purchased to serve as the power plant and two foils were carved out of timber. This hydrofoil vessel was extensively piloted and tested in the Charles River Basin. By analyzing this vessel's performance and documenting the design and construction process, hydrofoil technology will become more actualized, tangible, and accessible to the public.

Background

A hydrofoil while in flight is remarkably like that of an aircraft. Its motion can be described in the same three terms as conventional aircraft, pitch, roll, and yaw. Each one of these motions must be controlled for a hydrofoil to achieve and maintain steady flight. Pitch control, the angle of the vessel between its bow and stern, can be entirely handled by the design of the foils. If the center of gravity of the vessel shifts forward in flight, perhaps by a moving person, the bow will dip down decreasing the angle of attack for the forward foil, thus decreasing its lift. This decrease in lift will cause the bow to drop even further, however, the stern foil experiences the same change in angle of attack, also decreasing lift. This generates a phenomenon known as the weathervane effect, in which the pitch of the ship constantly changes as the foils generate varying amounts of lift due to changing angles of attack. As the bow drops, the angle of attack in the stern foil will decrease, causing the boat to level out again. This relationship however can quickly become dynamically unstable if underdamped. To generate a dynamically stable system, in which the correct pitch orientation is automatically return to, the forward foil must have a greater wing loading. Wing loading is the amount of lift generated, divided by the surface area of the foil. If the wing loading of the forward foil is to be greater than the of the rear foil, it must be orientated at a larger angle of attack to generate more lift. Since the angle of attack and therefore coefficient of lift is greater, equal changes in the angle of attack of both foils will result in smaller percent decreases in the amount of lift generated by the front foil.

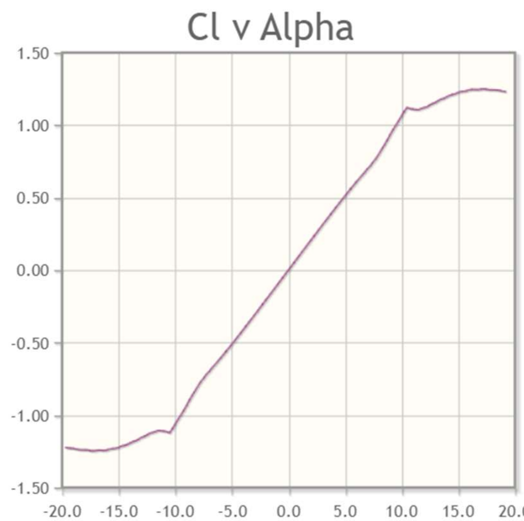


Figure 1: A graph displaying the relationship between the coefficient of lift of a hydrofoil vs its current angle of attack. Note, this is an unconventional foil shape, however, it is useful in conveying pitch stability as zero lift is produced at an angle of attack of 0 and it has a linear increase in lift. [2]

As can be seen in the graph, a decrease of one degree in the angle of attack from 10 to 9 degrees results in a small percent decrease, only about 10 percent, of the overall coefficient of lift. A decrease in the angle of attack for smaller alphas results in a greater percent loss of lift. For example, a change from five to four degrees results in a 20 percent loss. Therefore, when the pitch of the boat changes, the stern foil will be subjected to larger changes in lift than the forward foil which returns the system to a point of equilibrium after some period of oscillation. The water acts as a damper and the system will return to a point of stability, barring any further changes such as a changing center of gravity and waves hitting the hull.

Hydrofoils typically have three main categories of foil placement: balanced designs, conventional airplane style, and canard style. The balanced design where forward and aft foils support equal amounts of weight, conventional airplane style where most of the weight is supported by the forward foil, and canard style where most of the weight is supported by the aft foil. [3] Canard styles was the most suitable style for this thesis, because it has a history of success, is common in hydrofoil designs, and is suited for stern heavy vessels with outboards. Additionally, as previously mentioned, its beneficial to have the forward foil flying a steeper angle of attack which is therefore less efficient. Canard style foil placement increases overall efficiency by reducing the lifting reliance on the forward, less efficient foil.

Height control is another area of controls that must be mastered for hydrofoils to stay airborne. Hydrofoils produce enough lift to counteract the weight of the vessel and begin rising out of the water at their takeoff velocity. If a simple hydrofoil is accelerated beyond its takeoff velocity, it would seem to continue rising until it breaks the surface of the water, resulting in a loss of lift and likely crash back onto the waters surface. However, hydrofoils begin to lose lift as they approach the surface of the water in accordance with a submergence factor equation. The chord [m] is the distance between the leading and trailing edges of the hydrofoil and the submergence is the depth of submergence measured in numbers of chords.

$$F_s = 1 - 0.222 \times \left(\frac{(1.5 \times chord) - submergence}{chord}\right)^2$$

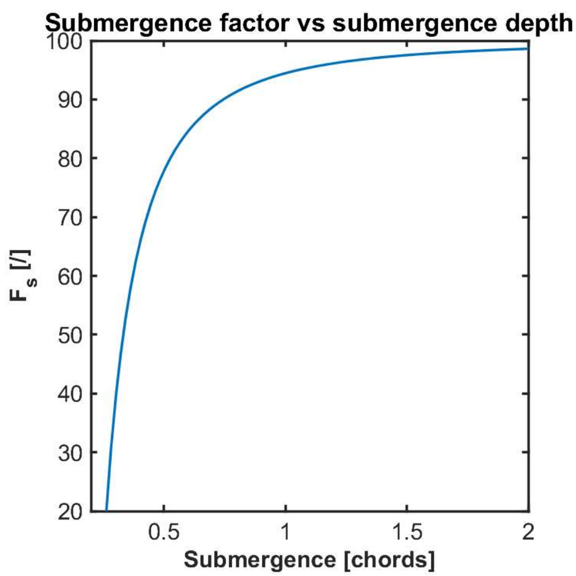


Figure 2: Graph displaying the relationship between the submergence factor and the submergence of the hydrofoil in terms of number of chords. This relationship was determined empirically and therefore, the equation breaks down at smaller submergence depths of less than 0.25 chord lengths.

As seen in the above figure, the most drastic losses occur when hydrofoils are submerged at a depth of less than one chord length. Staying below this mark ensures greater than 95 percent of lift is maintained. This phenomenon coupled with height sensing devices that actively adjust angle of attacks of the lead foil are common height controlling mechanisms for hydrofoils. Surface piercing hydrofoils that generate less lift due to less foil area as the vessel rises is an alternative, non-mechanical approach to height control and was the method employed in this thesis due to its simplicity.

Roll stability is particularly difficult for hydrofoils to achieve due to the vessel's center of gravity extending far above the lifting surfaces. Methods found on airplanes such as dihedral wings, are also effective methods for roll control in hydrofoils. These dihedrals apply a force above the center of gravity of the vessel, providing a righting moment whenever the vessel begins to roll. As the vessel rolls, these upwardly angles dip deeper into the water, generating greater lift as the opposite dihedral generates less lift. This force imbalance generates a right torque about the vessel's center of gravity.

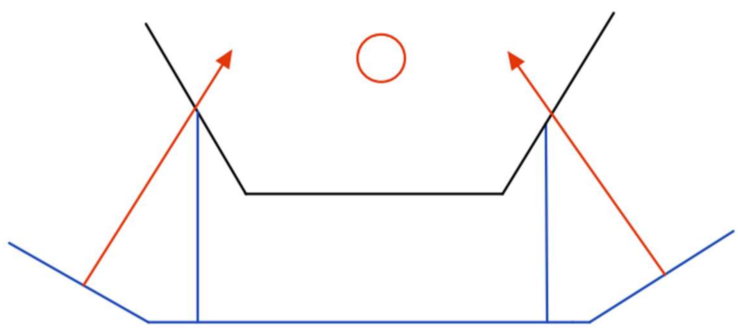


Figure 3: This schematic shows the stabilizing torques applied about the center of gravity from dihedral wings. The red arrows represent the force generated from the dihedral foil section and the red circle represents the center of gravity of the vessel. The black trapezoid is the boat hull and the blue lines are the foil structure.

Intuition regarding hydrofoils is extremely hard to develop as they perform in drastically different environments than their close relatives, air foil. Airplanes have large wings and fly very fast to generate the lift required for sustained flight. Hydrofoils however, have the large advantage of operating in water. Since water has a density 1000 times that of air, hydrofoils can generate 3 orders of magnitude more lift for a given foil at a given speed. Throughout the design and build process, it was constantly felt that the foils were too small and that foils with such small surface areas could never generate the 550 pounds of lifting force that was required. However, some intuition about hydrofoils can be developed from comparing them to common remote-controlled airplanes. Glider RC planes can typically fly at relatively slow speeds, as low as 10 to 20 miles per hour. These planes also have relatively large wings, sometimes measuring a wingspan of up to 1 meter across. If this example RC plane weighs only a half-pound, then this same wing, if placed in the water at the same speed, would be able to generate 500 pounds of lift which is roughly equal to the lift required for the project. Hydrofoils have the unique ability to lift such heavy weight because of the high density of water.

Our hydrofoil is planned to be canard style with roughly 70 percent of the weight supported by the rear foil and 30 percent supported by the front foil. The estimated takeoff weight is 550 pounds with a takeoff velocity estimated around 8 knots. The angle of attack for the front foil will be 6 degrees, with the angle of attack for the stern foil set at 4 degrees. The foils will be surface piercing dihedral foils to add in both roll stability and height management. The vessel was ceremoniously named ‘Heavy Drinker’ after it had to be towed back in after its second voyage as it had run out of gas.

Engine Rebuild

It was decided to use the largest available outboard engine to decrease the possibility of being under powered and unable to achieve lift. Using an overpowered engine would provide some margin of safety in the build of the foils and struts in case the handmade foils were not perfect replicas of their foil cross-sections. These imperfectly built foils would generate more drag and less lift than expected. Selecting a larger engine ultimately provides a larger room for error, as well as a larger range of angles of attack with which to achieve the necessary lift.

From the beginning, it was determined that this design project would only be affordable with a used outboard motor that was purchased non-running. Craigslist was the main source of possible motors and within the first week of the project, a dilapidated outboard that was remarkably cheaper than any of the other options, priced at only 100 dollars, had been sourced. The seller claimed the outboard had been sitting in storage for 2 years and had no knowledge of its operational history. Visiting the motor, the following morning, it was discovered the motor came with a single line gas tank, and control cables for the throttle and gear shifter. A visual inspection was conducted to determine whether the motor was fixable and to look for any visual defects. After verifying that the motor had no visible damage, it needed to be verified that the engine wasn't "seized", a relatively common condition in which the engine's piston stick to the cylinder wall and prevent it from moving at all, hence the term 'seized'. This failure is typically caused by insufficient oil lubrication, excessive RPM's, or general failure of internal components and often requires a complete and expensive engine rebuild. Fixing a seized engine was beyond the project's timeframe, budget, and tool accessibility. Placing the engine into gear and manually turning the propellor, indicated that the pistons were freely moving, and it was not seized. With these inspections, the motor was assessed to have a high chance of repairability within the allocated time and budget.

The power plant for the hydrofoil vessel is a 1953 Evinrude Super Fastwin 15 horsepower twin cylinder outboard engine. Evinrude has been making this line of engines for decades and the project was lucky enough to obtain the very first production year model, making the engine a 69-year-old vintage piece of technology.

Figure 4: The 1953 Evinrude Super Fastwin outboard motor when it was first purchased and placed on the motor stand.

These motors are highly sought after for their robustness, simplicity, and high power to weight ratio. The outboard weighs only 67 pounds, resulting in a power to weight ratio of 0.22 horsepower per pound. This impressive power to weight ratio is due to the motors remarkably simplicity and the weight savings of two-stroke engines. Two-stroke engines produce power every stroke and have the added benefit of not required complicated and heavy valve trains. In contrast to four-stroke engines, which have internal oil reservoirs to lubricate the moving internal parts, two stroke do not have internal oil reservoirs. Instead, two-stroke engines receive lubrication for their internal components such as the crankshaft bearings and cylinder walls from the fuel itself. The gas for two-strokes must be premixed with oil or else the motor will be unlubricated and fail catastrophically. These motors require higher than normal levels of premixed oil due to their old design. This motor requires a ratio of 24:1 parts of gasoline to oil for correct operation. Modern day two-strokes can operate on ratios as low as 100:1.

A motor stand was initially built for the engine out of 2x4's so that the motor could be properly worked on without it falling over and becoming damaged. A base measuring 24" x 36" was constructed to provide a stable foundation and then 30-inch upright 2x4's were added and a cross bar was attached to these uprights from which the motor could be mounted. Accounting for the motor's center of gravity to be offset from the transom mount by a few inches, the uprights were angled back 10 degrees and supported with additional 2x4 supports. With a proper motor mount constructed, the issue with the motor could now be properly identified and repaired.

With the cowl removed and the entire engine exposed, the pull starter unit was removed as the cord was very frayed and tangled. Replacing this cord with plastic coated 1/8-inch steel cable proved to be a mistake as the plastic coating on the inside eventually wore off and resulted in occasionally jamming of the pull starter unit. Swapping in a larger, 3/16-inch stainless steel pull starter cable fixed this issue. Additionally, the pull starter unit had a broken return spring.

Without this spring, the pull cord did not wind itself back up. After finding a suitable replacement, the new spring was installed with a generous amount of marine grade grease. The pull starter unit also struggled to engage with the flywheel often resulting in the motor not being cranked by pulling the starting cord. Adjusting the tightness of a bolt on the start housing increased the pressure on the pull starter engagement teeth eliminated this issue.

Figure 5: Left picture shows the frayed pull starting rope before disassembly. The right-hand picture shows the pull starter recoil spring installed inside its hubs. The spring had to be pretensioned to fit inside the housing and then generously coated in marine grease to reduce friction.

With the outboard now able to be reliably pulled, the root issue needed to be diagnosed. All motors, barring major structural issues, only need 3 things to be able to run. They need fuel, spark, and air/compression. Checking these 3 key requirements should be done systematically to prevent misdiagnosis of engine troubles.

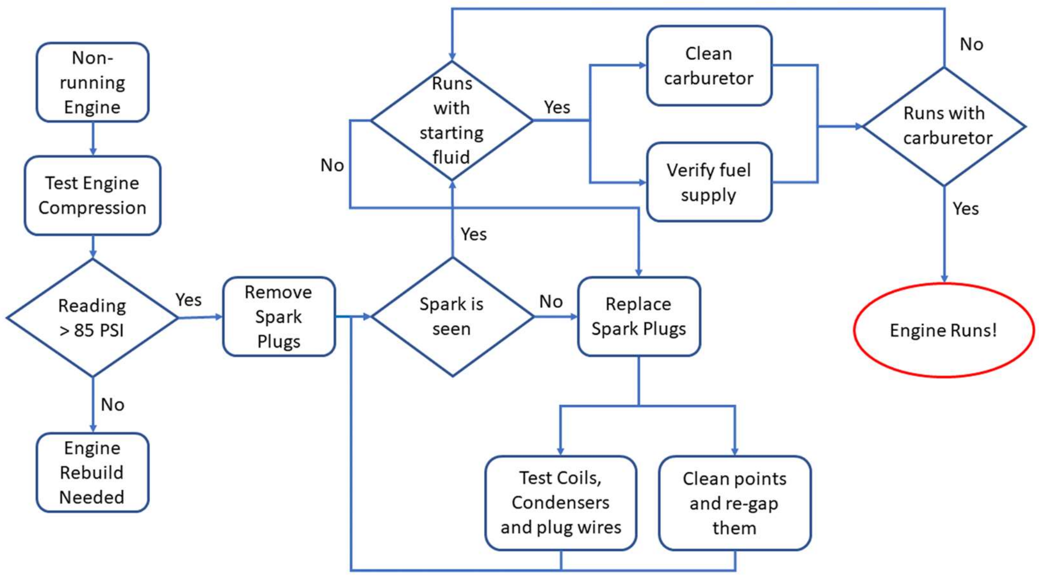


Figure 6: Schematic showing the flow process that should be followed when diagnosing a non-running motor. Failure to follow the flow process can result in attributing issues to the wrong parts.

This flow process for diagnosing a faulty engine was developed midway through the engine diagnosis and therefore, certain steps were done out of order.

Availability of air and compression was tested first. After removing the air box and confirming there was no obstruction, thereby proving the engine had access to air, the compression of the cylinders had to be tested. In a typical engine, the cylinders are compressed to about 100 PSI before ignition occurs and if the cylinder's liner or piston rings are overly worn, the cylinder is unable to pressurize and will be unable to sustain operation. Since this project did not have access to a cylinder pressure gauge to numerically test the cylinders, a qualitative test was used to test the compression. When placing a thumb over the open spark plug holes and cranking the engine, one should be unable to keep their thumb held over the open spark plug hole due to the building pressure inside. While not as quantitative, this test provides an adequate benchmark and can diagnose any major issues. Being unable to keep a thumb over the spark plug hole during the piston's compression, and with no difference felt between the two cylinders, it was deemed the pistons had healthy compression values. Therefore, it was confidently assessed that the engine had air and compression.

Fuel is provided by the carburetor and is often the most difficult to finetune. The motor had been sitting in storage for about two years so the fuel inside the carburetor would have dried by now and gummed up the carburetor passageways. Modern gasoline contains ethanol and when this gas sits too long, varnish is left behind that clogs the passageways, preventing them from working. The carburetor was removed, set aside for cleaning, and had a rebuild kit ordered for it. Starting fluid, which is aerosol gasoline, was then sprayed into the intake manifold of the engine in an attempted to start it. By replacing the function of the carburetor with starting fluid, it would be possible to diagnose whether the only issue was a faulty carburetor. Upon being unable to get the engine to fire, the engine had to be tested spark.

Testing for spark is done by removing the spark plugs, connecting them to ground and looking for a spark while cranking the engine over. Upon testing this, no spark was observed, indicating that the spark and electrical ignition had issues. Ignition systems on modern engines are controlled by a CDI box and the spark plugs are told when to spark by the computer. The spark plugs should typically spark when the piston is at the top of its ignition stroke, however, sometimes this spark is advanced or retarded depending on the current RPM's. On older engines, the spark is generated by a "point's system". A points system controls the spark by the opening and closing of a set of conductive contacts which are mechanically bound to the rotating crankshaft.

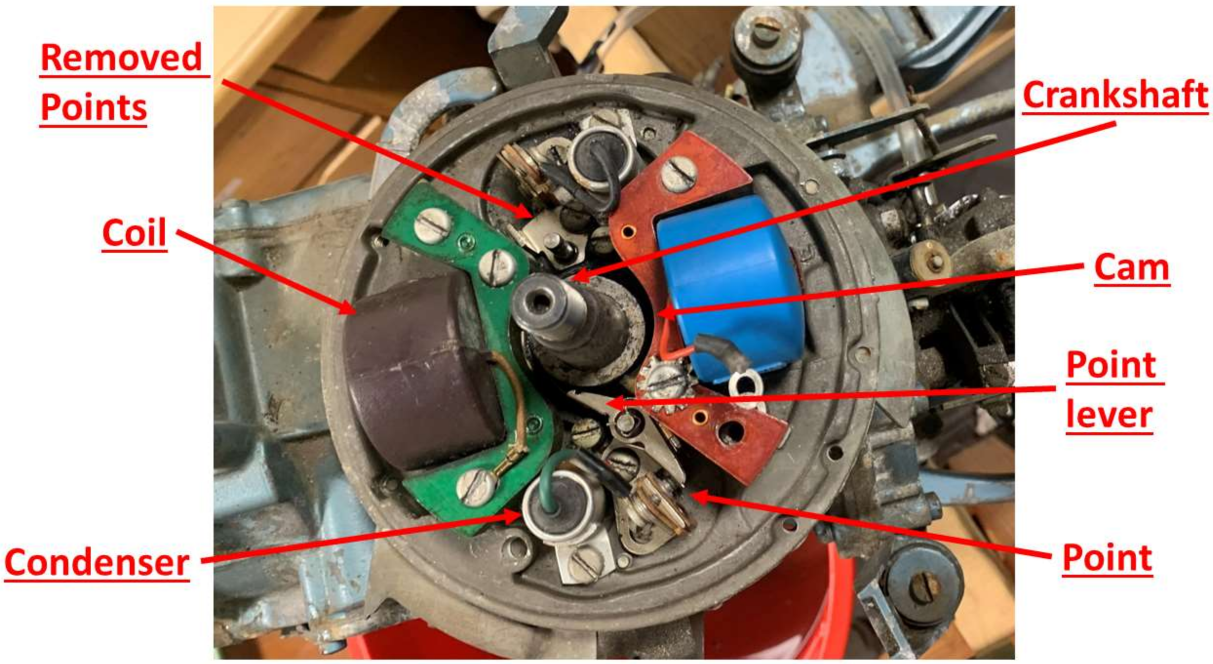


Figure 7: Annotated view of the stator plate which is responsible for the generation and timing of the spark. The high point on the cam (lobe) is blocked by the crankshaft in this image however the bottom set of points are just slightly open in the image.

This motor had two sets of points, each responsible for one of the cylinders. The crankshaft extends into the center of this assembly and has an elliptical shape. One side of points are in contact with this portion of the crankshaft called the cam, and when the high point of the ellipse touches the point's lever, it lifts one side up breaking the electrical connection. As the cam continues to rotate, the point comes back into contact with the other half and electrical connection is regained. Upon electrical connection, a surge of high voltage electricity is triggered and causes the spark plug to spark. Electrical coils on the stator plate are responsible for generating the electricity. These coils are stored inside of the flywheel and generate energy from the rotation of a magnet in the flywheel. These coils then send the power to the condensers which store the charge of electricity used for the spark.

The ignition system is contained entirely underneath the flywheel on the top of the engine. After removing the flywheel with a flywheel puller, the coils, condenser, points, and cam were are all exposed. It was immediately evident that the points were corroded and therefore could not move anymore. Since they were always connected to each other in this corroded state, a spark could never form. The points were removed, sanded down to remove all the corrosion and then replaced after being cleaned with acetone to ensure solid electrical connection. The points were tested by removing all other electrical components and then measuring the resistance between them when open and closed. When closed they measured under 1 ohm which is a satisfactory rating indicating a solid electrical connection. The coils and condensers were also tested using continuity electrical tests to test for any short circuits. At this point, the mistake of not resetting the point's gap was made and the ignition system was reassembled.

Within the ignitions system thought to be repaired, starting fluid was again sprayed into the intake manifold and the outboard engine roared to life for a few seconds. Assuming a faulty fuel supply, attention was next focused on rebuilding the carburetor. Modern engines today have electronic fuel injectors in which the onboard computer tells a solenoid valve when to open and for how long to add fuel to the air mixture. The fuel injectors spray a regulated amount of fuel directly into each cylinder and are very efficient but require the use of an onboard computing system. Older engines, before computers became common, utilize carburetors which regulate the flow of air into the engine and mix in the correct amount of fuel to allow the engine to run smoothly. Mounted in between the air intake, and the intake manifold, it mixes the fuel into the air by taking advantage of the venturi effect. As air flows into the carb mouth, also called the venturi, a suction force occurs, and fuel is sucked up through small tubes called jets. These jets draw fuel from a main reservoir or fuel bowl where a small amount of gas is stored, enough to run the engine for about 30 seconds. This reservoir contains a float that controls an inlet valve, allowing gas to enter the reservoir when the gas level gets low. This carburetor had only one main jet to provide fuel when under throttle. This jet is carefully sized to regulate the correct amount of fuel into the engine. This jet is finetuned by an adjustment needle which can be manually opened or closed to limit the fuel that can pass through the jet.

The carburetor also serves as a throttle with a butterfly valve inside the throat of the carburetor. At idle this valve is closed with small holes in it allowing just enough air by for idling. At idle the main jet does not provide any fuel and instead a separate passageway diverts fuel from the reservoir, up above the venturi then dispenses a small amount of fuel for the engine when idling. This passageway also has its own low idle adjustment screw which can finetune the fuel delivery for optimum engine performance. As throttle is applied, the butterfly valve opens and allows more air through, increasing the suction force, causing more fuel to flow into the air. Ideally the air fuel mixture will be kept at the ideal stoichiometry ratio, of 14.7 parts air to 1 part fuel. Over fueling causes the spark plugs to become wet with fuel, causing them to fail to spark. Too little fuel, called a lean mixture, can cause running issues and risks overheating the engine. If any of these small passageways or tubes are blocked, the engine will run poorly or not at all, so it is essential to be meticulous when cleaning the orifices.

Figure 8: This image shows the carburetor partially disassembled. Varnish is clearly visible inside of the carb fuel bowl and the cork float is partially dissolved.

Upon taking apart the carburetor, a substantial amount of varnish was found inside the main reservoir bowl. All jets, needle valves, and removable parts were removed from the carburetor body and set aside for cleaning. After several cleanings with carb cleaner, and vigorous brushing with steel brushes, the carb bodies were mostly clean of surface varnish. However, if any contaminants remain, they will be washed into the tight passageways and clog the carburetor later. Another method for cleaning the bodies is soaking them in a cleaner overnight to dissolve any containments in areas that could not be reached by hand. Commercial grade carburetor soaking cleaners exist however are corrosive, expensive, and meant to be reused several times. To reduce any negative impact on the financial budget and environment, it was decided to used Pine-sol, a mild detergent that was readily available on hand rather than a commercial grade, purpose built cleaner. Unfortunately, this was a mistake, as the Pine-sol cleaner left trace amounts of an unknown white residue, possibly from a mild reaction with the carburetor body. This residue was easily removed but it was noted that commercial grade cleaners should be used whenever possible.

All 'soft' components of the carburetor were removed and replaced by replacement parts in the rebuild kit. The original float was made of cork and was severely corroded from the ethanol in the gas. This was replaced with a new float made of fuel resistant plastic. All the packing washers, which help provide friction to the idle and fuel adjustment knobs and prevent air from leaking in past these screws were completely disintegrated. A pick was used to remove all remnants of the washers and then compressed air was used to blow out any residual pieces. The lower half of the carburetor body had a screw joint that had snapped off. Fixing this with JB weld proved to be a semi-permanent fix as this repair had to be made several times. Compressed air and spray carb cleaner was used to clean all the passageways in the carburetor body to an adequate level.

After attaching the recently cleaned and rebuilt carburetor, the engine was able to be started, but required many attempts, ran roughly, and struggled to stay running. Assuming a fuel issue since the motor was able to run intermittently, the carburetors removed and cleaned several more times. After hearing misfires in the engine when running, it was decided to expand the list of possible issues beyond fuel delivery. The flow chart showed in figure 5 was then made to systematically approach the possible issues and it was determined that the spark must be behaving poorly. It was decided to test the timing of the points, a crucial adjustment that had been initially overlooked. The timing is responsible for when the spark fires and while the cam lobe determines this, the width the points open will also influence when the spark is triggered. The timing can be checked by using a set of feeler gauges to determine the exact distance that the points open. These points were supposed to be gapped at 0.020" with only slight resistance when sliding a 0.020" feeler gauge in between the points. It became immediately evident that one of the points was very poorly gapped and had closer to the 0.030" of gap. This extra-large gap was causing the spark to fire at the wrong time resulting in the poor running and misfires observed in the engine. After setting these points to the proper 0.020" gap, the motor fired up first pull and began running great.

While this is acceptable to get the engine running, there is a more precise method of setting the timing that guarantees the greatest engine performance. Rather than mechanically setting the gap, a multimeter is attached to ground and to the positive side of one of the points. This can show exactly when the point opens, which is when the resistance jumps from 0. This jump should occur when the timing mark on the fly wheel lines up with the timing mark on the stator plate. This ensures the points are perfectly adjusted for optimum performance.

Finally, general maintenance was performed on the outboard to optimize its performance and reliability. The water impeller, responsible for pumping cooling water throughout the engine was replaced with a new pump kit.

Figure 9: Side by side comparison of the old water impellor on the right and the replacement impellor on the left. Made from flexible plastic for optimum pumping, the impellors harden over time reducing their efficiency. An arm on the old impellor broke off shortly after removal from the engine.

The new impellor had to be twisted to fit into its housing as can be seen by the plastic deformation in the old impellor. Care was taken to ensure the drive shaft, on which the impellor sat, was turned clockwise during this seating operation. The driveshaft turns clockwise during normal operation of the motor and placing the impellor in backwards would result in severe damage and ineffectiveness of the water pump.

Finally, an alternative fuel delivery system had to be constructed. The original fuel delivery method utilized positive air pressure from the engine's crank case to pressurize the fuel tank and push gas into the carburetor. The gas tank that came with the motor however was not pressure rated and therefore could not be used in the traditional fashion. Deterred by the prices of pressurized fuel tanks, a diaphragm fuel pump was installed on the engine to provide fuel delivery to the carburetor. Diaphragm pumps work by using alternating positive and negative pressure to flex a membrane that pumps fuel. The engine already had a nozzle for providing positive pressure which could be modified to provide alternating pressure. The intake manifold was removed exposing two holes, one for each cylinder, with a flexible stopper over them.

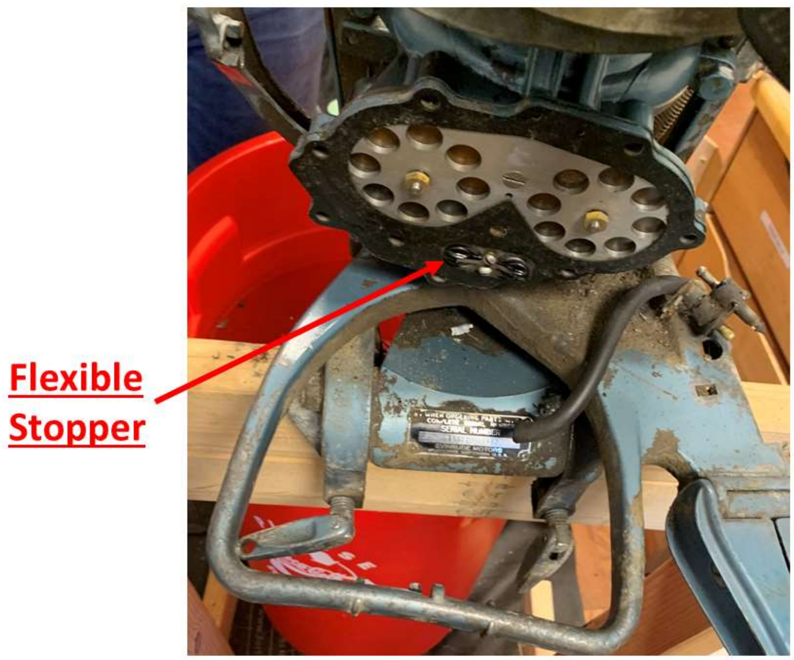


Figure 10: The rubber stopper can be seen here covering both pressure holes. This part was entirely removed from the engine.

Designed to seal the hole when negative pressure was present, this flexible stopper was removed and one of the holes was plugged by a vacuum tube stopper. Now the remaining one hole provided positive and negative pressure consistent with cycle of the piston, allowing operation of the diaphragm fuel pump.

Boat and Hull Design

The ‘Heavy Drinker’s hull had to satisfy several requirements. Most importantly it had to be exceptionally strong and durable. The main issue when foiling is that an occasional rogue wave hitting the hull will change the angle of attacks on the foils great enough that it cannot recover, and the boat will crash into the water from its foil height. This is done at high speeds so the hull had to be able to withstand constant impacts with water up to 8 inches in height while at speeds more than 20 miles per hour. This high stress condition made it imperative to design a hull that was extremely durable. The hull also needed great rigidity to prevent damage to the epoxied seems. Too much flexing would cause the brittle epoxy to crack and the boat to develop leaks. It also had to be relatively lightweight to allow for easy transportation to the river for testing and even more importantly, be light enough to foil. While the hull design process was being carried out, the power plant had not yet been selected so minimizing weight in case of an underpowered power plant was crucial. However, it was decided that the vessel should be large enough to enjoy with relative stability.

To achieve high structural toughness, we designed a system of runners and cross supports to support the boat floor and sides at all locations. The number of cross supports was increased from three in the original plans, to five, to better distribute the load and because the hull was longer. These were to be interlaced longitudinal runners to provide maximum rigidity and support.

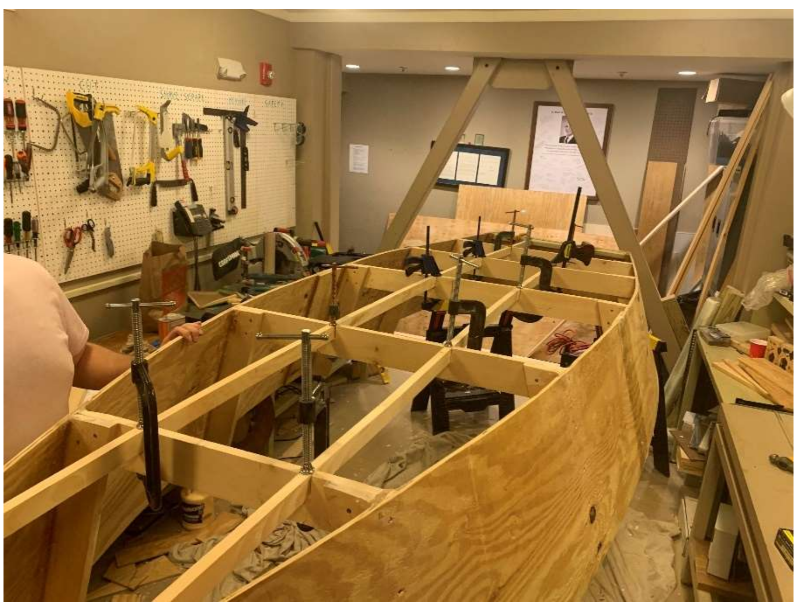
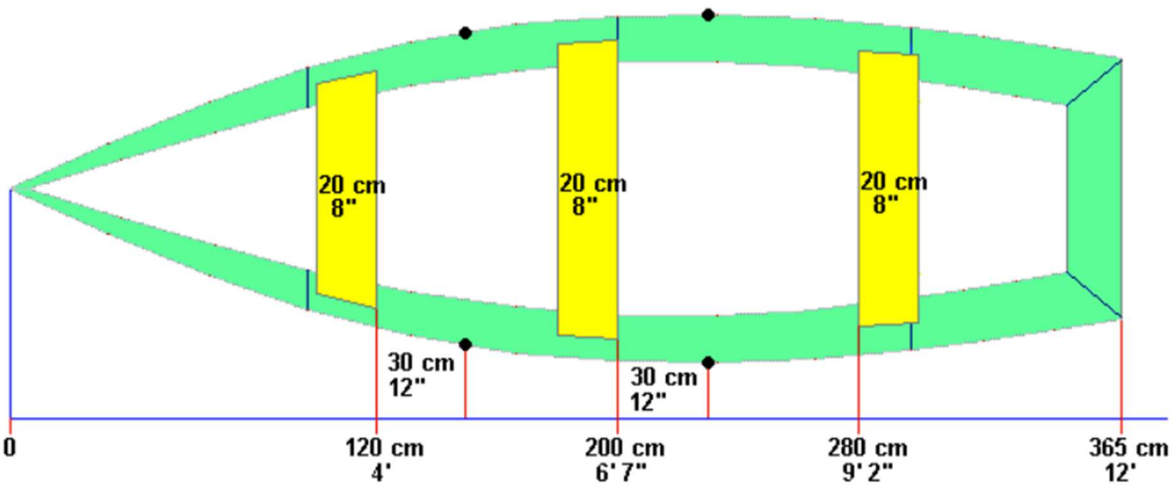


Figure 11: The lattice of runners and cross supports can be seen here. The longitudinal runners fit into slots inside of the cross supports and then were glued in place to create a rigid structure.

These runners were expected to provide increased stiffness to the floor, which is critical to preventing cracking at the chines. If the floor can flex, this places high stress on the wall and floor interface leading to cracking and inevitable leaks in the boat. This lattice of supports would also serve to create a series of 15 separate, watertight compartments distributed equally through 5 bulkheads. This would help in the event of leakage or water coming over the sides by isolating the water to each effected bulkhead. The water in these bulkheads could then be pumped out easily, without large swaths of water spreading out in the boat and being difficult to pump.

The hull was to be constructed mainly out of 4x8 foot sheets of 3/8” inch CDX plywood sheets and 10-foot sections of wooden planks to serve as reinforcing struts. 3/8” inch thick plywood was chosen over ¼” plywood for the added strength it provided even with the increase in overall weight.

We took great inspiration from Hannau’s Boatyard, a website that provides free boat plans and techniques on basic boat construction. We modeled our hull design plans on his 12-foot skiff plans and while we changed most of the dimensions found in the boat, the basic build flow and techniques were employed in our construction.



[4]

Figure 12: The original dimensions from Hannau’s boatyard are displayed above. The length was increased to 14 and a half feet, the beam increased to 54 inches, and the taper in width towards the stern was made less drastic.

While this project required a greater displacement vessel, increased stability, and increased strength, all these modifications were easy additions to the base design. As a tradeoff, the vessel would be heavier, and create more drag than the previous design but the high-powered outboard was deemed powerful enough to take care of these increases in drag.

Our build area, the maker space inside the fraternity of Phi Beta Epsilon was greatly suited to our needs. It received little use so the boat could be stored inside the room while under construction and it had few self-standing machines, so much of the room was open floor space for the hull. The hull would be unable to leave via the door when finished due to geometry restraints and therefore the hull would have to be removed via the window. The window measured 60” x 36” and therefore provided our only hard constraint. The maximum width of the boat could be at most, 60 inches, and the hull could be no taller than 36 inches. While the height was not an issue, was settled on a width of 54 inches to provide as much width as possible while leaving a margin of error for boat extraction. Boat width was maximized to increase the stability of the boat when afloat and maximize floatation.

The US Coast Guard determines what size outboard motors can legally be put on small boats to maintain safety. [5] Since a motor had not yet been sourced during hull design, it was determined to design the hull to be able to accept the largest listed outboard on the USCG chart to expand the list of potential outboard engines that could be used.

$$Factor = Boat\ Length \times Transom\ Width$$

This is the equation used by the US Coast Guard to place small boats into categories that determine the maximum size outboard they may install. To qualify for the maximum outboard horsepower rating of 15, the hull needed a factor of 46. To satisfy this requirement, the length of the hull was set at 14' 6" so that a factor of 46 could easily be reached even with a modestly narrow stern. Given that our stern was 48 inches across at its widest, our hull has a factor of 66, well above the minimum required by the USCG.

The sides of the hull had to be 14' 8" inches long to preserve the shape of the original boat design that was being referenced. One of the most important aspects to preserve was the streamline curve of the hull's sides. If this natural curve was not kept, the walls would bow outward into the water and generate excessive drag. Therefore, much care was taken to design each cross support, which set the beam of the boat at that location, to be the correct dimension. In the bow of the boat, the beam widened the fastest and slowly this widening grew less as the maximum beam of the boat is approached. To prevent the walls from bowing out, the second cross support had to have a greater increase in width from the first cross support than the third cross support has from the second cross support. The opposite was true of the cross supports to the stern of the maximum beam, set by the third cross support. The boat had to widen fastest by the bow, then gradually stop widening and eventually curve in slightly after the maximum beam. If the rear most cross section did not taper in more than the second rear most cross section, then the streamlined walls would become wavy and produce much more drag.

Much thought was made about whether the stern should be narrower than the maximum beam or not. A narrow stern allows water to flow back together, generating a less severe break at the stern and reducing drag. However, it reduces the flotation available in the stern and since an outboard was being mounted, there would be a significant amount of weight in the stern. After testing the vessel in water, it has been decided that the stern could have remained wider and did not need to angle in as much.

Since the maximum width of the hull had been increased, the angle the bow meets itself was also increased. The original plans called for a bow stem of only 50 degrees, this angle was increased to 58 degrees to better accommodate the wider beam and to generate more width as quickly as possible. Additionally, the bow was angles forward aggressively to help aid the hull in cutting through the water. The side walls were 23 inches tall at the bow and the bow tapered forward by 9 inches, giving the bow a forward lean of 21.3 degrees.

Displacement hulls, those that achieve all buoyancy purely through displacement, are severely limited in the maximum speed they can achieve by their hull speed. When boats are underway, they push water out of the way of the bow and this water will build up on itself, called a "bow wave". The faster the vessel goes, the higher this water builds up as the hull seems to be climbing up this column of water at the bow and sinking in the stern. At this condition, it's extremely hard for the vessel to go any faster and this speed is called the hull speed. Hull speed is a property unique to every boat and is determined by the wetted length of the vessel. [6] v_{hul} $\left[\frac{m}{s}\right]$ is the maximum speed the hull can travel and L [ft] is the total length of the boat.

$$v_{hull} = 1.35 * \sqrt{L}$$

As can be seen by this equation, hull speed is a limiting factor to small, hulled vessels such as the 'Heavy Drinker'. The hull speed for the 'Heavy Drinker' is only 5.14 knots. To achieve speeds greater than this, small boats will typically start 'planning' to go faster. The bow is naturally pushed up by the water when the vessel picks up speed and these two upward forces help lift the boat up into plane and glide over the water. A boat's ability to plane, especially small boats is critical to achieve high speeds and low fuel consumption as planning use drastically less power since the hull rides on top of the water, like a hydrofoil, instead of pushing through the water as a typical displacement hull would.

The transom was designed to be angled inwards by about 17 degrees. By having a transom that has a negative angle, a greater range of angles is provided for trimming an outboard motor. Trimming a motor is when the angle of the outboard is adjusted to obtain the best boating characteristics. Typically, an outboard will be 'trimmed' and angled downwards to help push the stern up and push the bow down to get into plane.

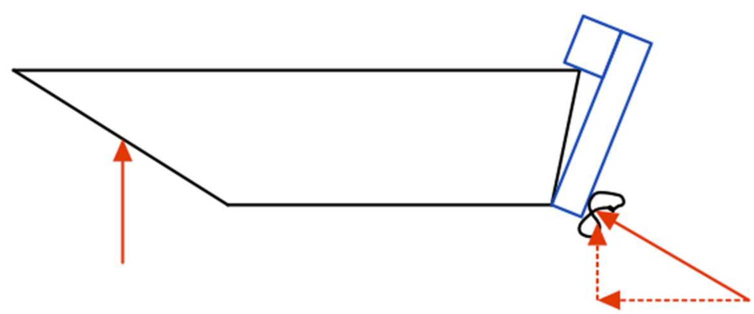


Figure 13: This schematic shows the upwards forces involve with lifting a hull onto plane. The forces, symbolized by red arrows, are generated by deflection of water in the bow, and the negative tilt of the motor in the stern.

There's are several different modes of drag on a vessel's hull. The most noticeable is wave making drag which is generated whenever a vessel's hull produces waves or leaves a wake. The energy needed to disturb this water is considered the wave drag. Form drags, generated from forcing the hull through the water and viscous drag, generated from the friction between the water and the hull are two other large sources of drag. Typically hull drag is measured by having another boat tow the vessel to be tested with heavy duty spring scale in between the tow ropes. The measurement on the spring scale indicates the drag present at any given speed and using the drag equation, a coefficient of drag can be determined to calculate drag at any speed.

$$Drag = C_D \times A \times \rho \times \frac{v^2}{2}$$

Unfortunately, a spring scale of an adequate size was unable to be procured so rough drag estimates can be calculated from Hannau's boatyard's website. [7] They provide a drag vs velocity graph for their boat design that can be used as a rough base for estimating the drag of the 'Heavy Drinker'. The 'Heavy Drinker' has a wider bow stem, wider stern, and a heavier load of 550 pounds instead of the original 330-pound load case. Therefore, a scaling factor must be used to calculate reasonable drag estimates for our hull design. A, upper limit of 1.4 was considered safe to estimate the upper drag the boat would.

By examining the provided drag curve at velocity values of 2.05 m/s, 3.025 m/s and 4 m/s, a coefficient of drag can be calculated. However, since only the coefficient of drag and wetted area will change between the hull design found on Hannau's Boatyard and the 'Heavy Drinker's hull, a variable encompassing both coefficient of drag and wetted area was calculated to reduce any propagation of errors from occurring from inaccuracies in estimating the change in wetted areas between the two hulls. After inputting the drag values at the three respective velocities, the drag coefficient and area factor equaled 0.035. Substituting this value into the drag equation and multiplying by the scaling factor of 1.4 accounts for the less hydrodynamic profile, and the increased wetted area due to increased weight. With a hypothetical coefficient of drag calculated, a graph of the hull's drag was made, shown in Fig. 12.

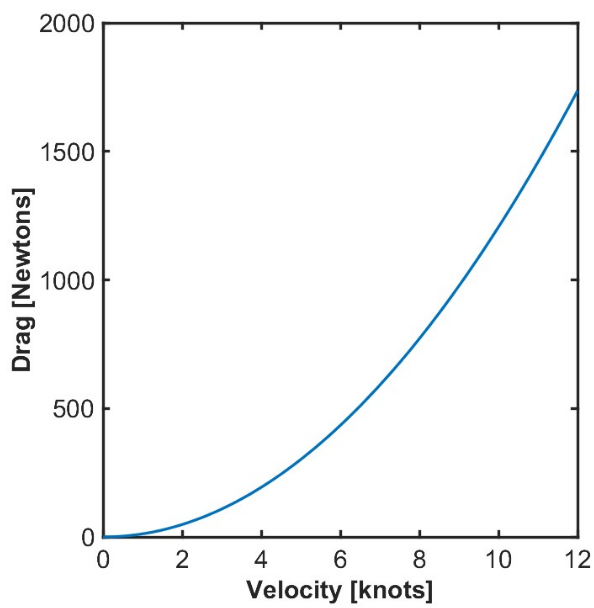


Figure 14: This graph shows the exponential relationship between the hull drag and the hull's velocity for non-planning situations.

These calculations allowed a hypothetical drag for the hull to be calculated without access to proper drag calculating equipment. While not precise, a drag value for the hull was required for the foil design and outboard power considerations. It is also worth noting that while this graph is suitable for estimation purposes since the hull will not achieve planing speeds before the hydrofoils lift it out of the water, this graph cannot be extrapolated as it does not include the proper dynamics concerning how drag is affected when the hull begins to plane. Drag will reduce drastically as the hull begins to plane so this graph is only applicable to velocities below planing speeds, approximately those shown on the axis.

With a theoretical calculation completed for the hull, estimations for the power requirement can be completed as well. With the equation for power being as follows. Power required increases with the cube of velocity [m/s], and depends on the drag [Newtons], rapidly requiring more power at higher speeds.

$$Power = Drag \times v$$

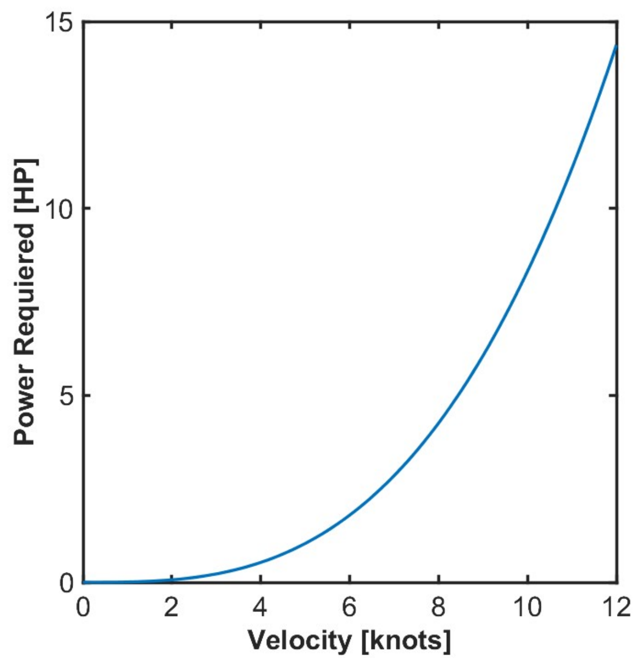


Figure 15: The graph shows the required shaft horsepower needed for propel the hull at a range of velocity. As with the drag graph in figure 10, these values are only valid for non-planning and non-foiling speeds so extrapolation of data cannot occur.

Fig. 15 shows the cubic nature of the power requirement. The power requirement is expressed in terms of the power that is transferred to the water in the form of propulsion. Due to inefficacies in the outboard drive train, and efficiency limits of propellors, the overall propulsive efficiency, OPC, is typically around 50 percent. This OPC must be multiplied by the power plant's rated power to obtain the real propulsive power that is charted in the above graph. Therefore, the 15-horsepower outboard present on the hydrofoil, is only able to generate 7.5 horsepower of propulsive efficiency which limits our theoretical top speed top just under 10 knots.

Finally, to determine whether this outboard engine will be sufficient to power the hydro craft, calculations were performed to determine the required take off velocity based on the lift required. $C_L$is experimentally determined, ρ is the density of water, 1000 $\frac{kg}{m^3}$, A $[m^2]$ is the area of the foils, both F_{ar} and F_s are unitless factors relating to submergence and aspect ratio of the foils. This can be graphed to display the required velocity necessary to generate enough lift for takeoff.

$$L = C_L \times \rho \times A \times \frac{v^2}{2} \times F_{ar} \times F_s$$

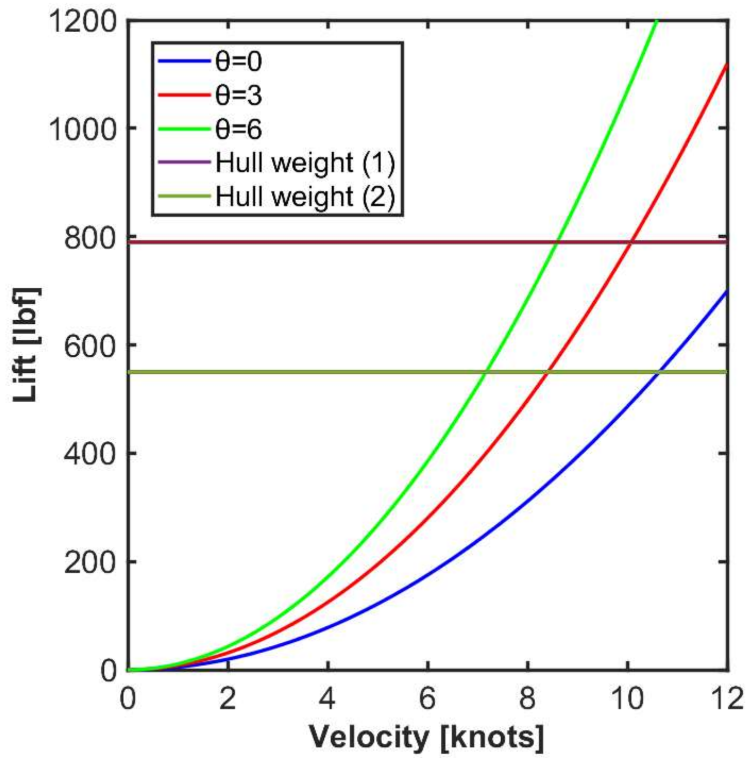


Figure 16: This graph displays the velocities required for generating enough lift to achieve flight for angles of attack ranging from 0-6 degrees and for two load cases. Hull weight (1) is the loading conditions for one passenger and hull weight (2) is the loading conditions for two people. Take off velocities for 1 passenger range from 7.1 knots, 8.4 knots, and 10.6 knots depending the average angle of attack of the foils.

These velocities can be used in figure 14 to determine the required engine size to achieve lift. Comparing the two graphs shows that the hydrofoil will be able to achieve flight for both loading scenarios at all angles of attack plotted except for an angle of attack of 0 with two passengers.

Hydrofoil Manufacturing Process

The hydrofoils are constructed with wood due to ease of construction and low cost. Despite being cheap and easy to work with, wood is weaker than most other materials suitable for hydrofoil construction, so great care was taken when selecting the hydrofoil cross sections. The wood was also coated with epoxy and reinforced with fiberglass.

Several options existed for how to begin the foil construction from wood. One option was to laminate sheets of plywood together with wood glue to develop a rough cross section of a foil and then sand it into the foil shape. However, it was decided that wooden beams were a good candidate as a base material since they did not require any prep work and could be selected with different dimensions. Since the front foil was smaller in area, a 2x6 was selected as being a suitable shape in which the hydrofoil cross section would fit and a 2x10 was selected for the rear foil. From here, the boards were cut into the correct lengths of 36 inches and 48 inches respectively and then cross sections of the foil shapes were printed out. The foil cross sections were obtained at the website, air foil tools. [8] These cross sections were sized to fit the width of the boards cross section and cut out. Each cross-section cutout was held to either end of the board and traced over with a sharpie. After this the outline of the hydrofoil cross section was highlighted by black sharpie.

Initially the excess wood outside this foil outline was removed with repeated passes by a circular saw. The depth of cut would be set to just above the outline and then the width of the saw blade in material was removed with each cut. Each consecutive saw pass would occur slightly to the side of the original pass. While effective, this required roughly 60 passes for the rear foil and was very time consuming.

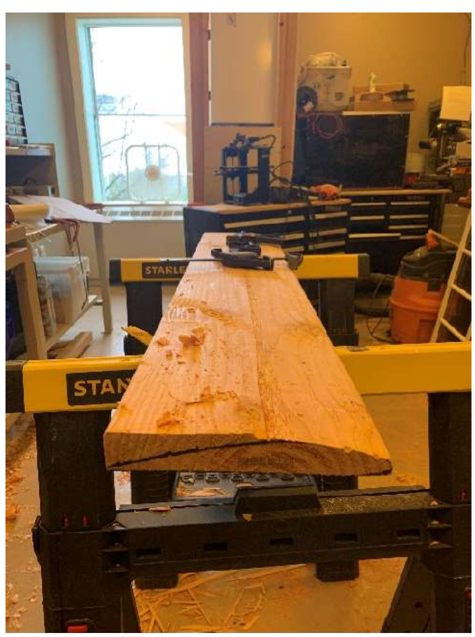


Figure 17: The aft foil during the shaping process. The outline of the foil cross section can be seen on the end of the board.

A handheld electric planar was later used to remove the bulk excess wood and became the preferred method due to its rapid material removal rate. Once within proximity of the foil outline, a handheld plane was used for the fine details and work. The foil cross section was also cut out of small sections of wood to act as a guide to check the foils with, but these proved too cumbersome to be of use. Visual inspection was used to detect any irregularities resulting in foils shaped with remarkably accuracy.

The foil cross section selected for our foils was the NACA 4412 cross-section as recommended by Ray Vellinga in his textbook. [9] However, when the front foil cross section was being sketched onto the 2x6, it was observed that this foil would be excessively thin. Foil cross sections are numbered according to their physical dimensions. The last two numbers of our selected foil shape, NACA 44XX, describe the width of the foil at its widest in a percentage of the length of the foil. Therefore, the original foil design called for only 12 percent thickness. This was changed last minute to a thicker design.

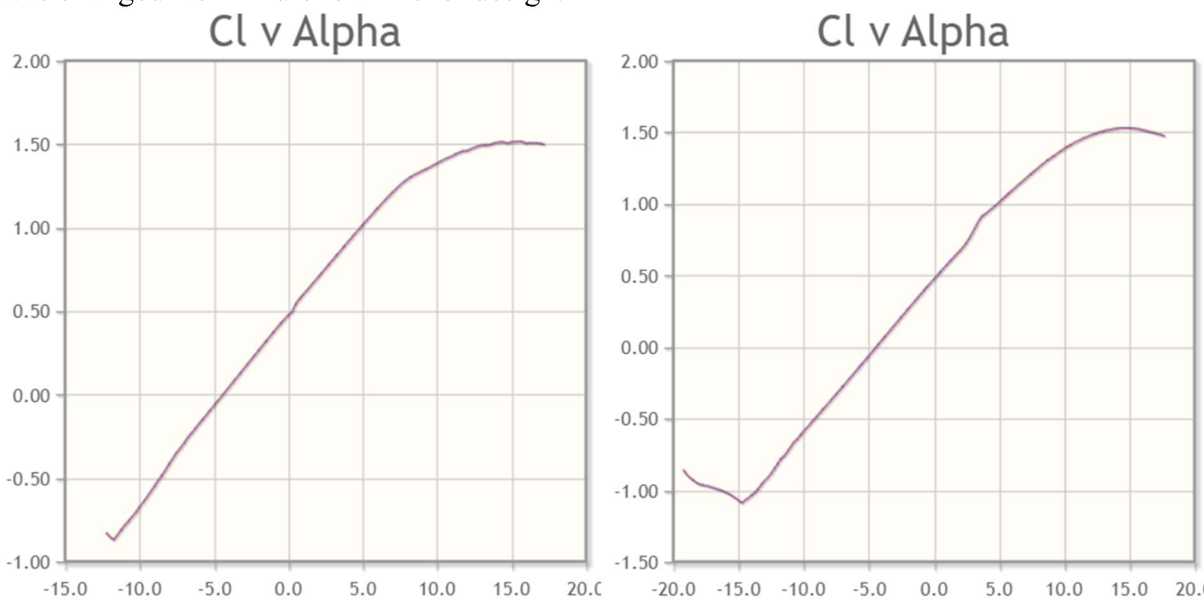


Figure 18: The left graph shows the relationship between the coefficient of lift and angle of attack for the NACA 4412 foil. The graph on the right shows the same relationship for the similar NACA 4418 foil. Both graphs were developed with a Reynolds number of 500,000 which is close to our estimated Reynolds number of 450,000 at takeoff velocity. [10]

After reviewing lift and drag graphs for a variety of thickness, the NACA 4418 foil was selected as a good combination of thickness and lift characteristics. Since the vessel will be hydro foiling in water, rather than air, the Reynolds number remains high despite slow velocities. After comparing the two foils, it was determined the thinner foil NACA 4412 while much more efficient at low Reynolds numbers, had a similar performance the NACA 4418 at the Reynolds numbers to be encountered in hydro foiling.

To achieve dynamic stability with our dihedral foils, it was calculated that the foil dihedrals had to be attached at an angle of 40 degrees. A chop saw was used to cut these edges at the correct angle, glue was applied, and they were fitted together by hand. After ensuring alignment visually, the wings were temporarily secured in place by a nail gun. A combination of 2 ¼” screws and ½" wooden dowels were used to permanently secure the dihedral wings to the main foil.

The struts for the forward foil were built out of 2x6's and the struts for the stern foil were built out of 2x8's. The same process used for the foils was employed for the struts. However only 19 inches of the struts was shaped into a foil design. This was to leave as much material as possible for additional strength, and to ensure a flat mating surface between the foil strut and the boat. 19 inches was determined to be the ideal number after considering how much of the strut may be in the water at any given time. The foil will have to remain under the water at least one chord length to maximize lift characteristics and the hull was planned to rise six inches out of the water while foiling. Additionally, the hull may be sitting in the water by up to 2 inches in the bow before liftoff. Therefore, up to 14 inches of the vertical strut was expected to be in the water. An additional 5 inches was added for a safety factor as well as to account for any lost material when the struts were attached to the foil. The stern mounted foil, with a chord length 2 inches longer than the bow foil would have to remain 4 inches deeper in the water. Therefore, it was assumed that 18 inches of its struts could be exposed to water and so the strut had 20 inches of its length shaped into a foil design. The forward foil vertical struts measured 32 inches long and the rear foils were 36 inches long.

The struts then had the upper half of the foils cross section sketched onto them at the bottom. This outline was then cut and sanded down so that the struts matched the contour of the main foil.

Secondary side struts were also used, supporting the outer edge of the dihedral wings to the vertical struts. This was done to relieve the stress on the joint between the main foil and the dihedral wings. These struts were made of left over 2x4's and utilized the same NACA 0021 foil shape as the vertical struts. To account for the smaller size of the 2x4 however, a more drastic taper was used in the rear of the foil cross section. At most, only up to 4 inches of this strut would be in the water so strength was optimized over improved foil and drag characteristics and only 6 inches of the side struts were formed into foil shape.

It was preferred to have the side struts meet the vertical strut at a flat, non-shaped section to ensure a solid fitment. However, the side strut couldn't meet the vertical strut too high or else it would get in the way of the attachment bolts. Therefore, it was decided that the side struts should come off the dihedral wing at an angle of 40 degrees to the horizon. This ensured the side struts meet the vertical strut at an optimum height.

After performing stress calculations, the wood was determined to just satisfy the strength requirement for the heavy lift cases. To develop a safety factor, the foils were fiberglassed and epoxied for additional strength. Fiber glassing, also known as glassing, can add great strength to objects. First a 2-part marine grade epoxy was mixed and then lightly applied to the foil surface. Then 6-ounce fiberglass cloth was applied and coated with more epoxy. Once dry, this fiberglass and epoxy resin combination was hard and significantly strengthened the foils. Additional layers of fiberglass were applied at the dihedral wing connections for added strength. Care was taken to avoid sharp bends in the fiberglass as this would inevitably lead to stress concentrators. The fiberglass also helped ensure a smooth finish on the foils and struts to minimize drag.

Figure 19: The forward and aft foils shown on the right and left side respectively.

The fiber glass was initially laid so that the parting line where the ends of the fiber glass sheet met was in the middle of the foils top surface. It was initially thought this would help provide a smooth transition between layers of fiberglass. However, it was discovered that this led to the fiberglass pulling up and away from the surface of the foils are the trailing edge, resulting in bubbles forming underneath the fiberglass, reducing the smoothness of the surface.

Another method, by which the parting line of the fiberglass meets at the trailing edge was also tried with much greater success. This method eliminated the issue of wrapping the fiberglass sheet around the tight radii of the trailing edge and resulted in much smoother fiberglass drying. While these foils had imperfect cross sections and slightly bumpy fiberglass overlayed on them, they were still expected to perform well. Coefficients of lift were expected to be decreased and coefficients of drag were expected to be increased but the foils were of adequate quality that this diminished performance should not be an issue.

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The tops of the vertical struts had 7-inch long 4x4 blocks attached to them with a combination of glue and screws. These blocks were shaved down to fit the curvature of the outside of the hull. The foils were placed onto the vessel and mounting holes were drilled to allow for varying angles of attack of the foils. The hydrofoil’s angle of attack is intended to be quasi-variable so that steeper or shallow angles of attack can be employed depending on how testing goes. One bolt hole was placed near the top of the struts and was the axis about which the rest of the foil rotated. Three separate holes were placed lower on the strut to allow for 0, 3, and 6 degrees of angle of attack.

Water Trials and Conclusion

Initial sea worthiness trials proved the hull to be much stiffer than initially expected. The longitudinal runners in the floor worked as expected and are responsible for the rigidity of the floor. As discussed earlier, this stiffness in the floor is critical to preventing cracking in the fiberglass at the floor and wall interface. The hull experienced light leakage in only two forward bulkheads. Both leaks were very minor and only leaked a few cups of water every roughly 30 minutes and only when the boat was heavily loaded with more than 550 pounds.

Figure 20: The ‘Heavy Drinker’ pictured in the water at the MIT Sailing Pavilion

The vessel also exhibited exceptional stability. Standing in the vessel while underway or at rest is easily permitted and does not roll the boat greatly. Attempts at tilting the boat have shown a near impossibility to tip the hull while seated in calm conditions. However, some slippage across the water seems to occur when the boat is turning through moderate to heavy winds. This horizontal motion while qualitatively felt, is almost impossible to quantify. This issue was most likely the result of an inadequate keel however was deemed not substantial enough of an issue to constitute any modifications to the keel which would have required the removal of the hull from the water and docks.

On the maiden voyage, 4 individuals were onboard for the initial testing resulting in about 1000 pounds of passenger cargo. Due to initial improper weight distribution, the bow rode too low in the water and some water spilled over the bow when going moderate speed. Water also spilled over the outer rear corner of the vessel when performing sharp turns. This spillage was most likely due to the heavy loading conditions as well as the boat was not able to properly bank into the turn in time. No water spillage other than spray over the bow has occurred since the maiden voyage.

The steering system encountered constant problems during the first week of water trials. Issues ranging from snapped steering wheel axles, snapped rope, and excessive slop in the steering wheel proved detrimental to the control of the boat. The rope used to steer the motor often loosened, adding up to ¾ of a full turn of the wheel of slop between direction changes. The axle also snapped due to improper rigging of the control lines which contributed to excessive downwards force on the steering wheel axle. The steering linkages had originally been routed from the bottom of the center console up to the wheel axle. This placed the tension of the steering linkage rope in line with each other, so the steering wheel axle had twice the tension force pulling down on it, generating a substantial torque. By routing the steering linkage rope farther up, the two ropes approached the steering wheel axle from almost opposite directions, canceling out the forces and generating much less torque. It was also decided to switch from nylon rope to steel cable as for the steering linkage for a variety of reasons. The biggest reason was that the steel cable would not stretch at all, eliminating much of the slop in the steering system.

Initial sea trials encountered a few issues. On the first voyage from the sailing pavilion, the vessel ran out of gas a few hundred yards away from the dock. After receiving a tow from the dock master, the inspiration for the vessel's name, 'Heavy Drinker' was coined after its excessive fuel usage. Other learning points in the first few days of sea trials was the imperative need to only start the outboard while in neutral. Accidently failing to heed this rule, the boat was once started in forward gear with the throttle set high. Immediately accelerating the vessel had been pointed at the sailing docks and was only about 25 yards away when the outboard was started. While the engine was killed in time, the vessel still struck the dock at an excessive speed, however no one was hurt nor was any part of the vessel or docks damaged.

Issues with the fuel pump have also persisted so the operator has been required to pump the fuel by hand while underway. Additionally, full throttle sometimes causes the outboard to react with varying bursts of power, so the throttle is typically limited to about 80 percent of full power. With this throttle application, the vessel attains a speed of about 12 miles per hour with two passengers, with foils not attached.

Figure 13, obtained from an estimated coefficient of drag and area factor from a different hull and scaling factor lines up with experimentally obtained results remarkably well. With two individuals on the boat, a slightly increased load, the hull topped out at 11.5 miles per hour without planing. While this speed was initially thought to be too low, and the engine's power output was called into question, Fig. 11 corroborates that the speed was correct. 11.5 miles per hour is equal to 10 knots which corresponds to a power requirement of 8.2 horsepower. Despite several assumptions, this power graph correctly estimated the top speed of the hull within 9.3% accuracy. The graph is slightly conservative, overestimating the power requirement slightly, most likely due to the conservative scaling factor of 1.4 that was chosen.

The vessel has been taken out and successfully achieved flight on the morning of May 12, 2022, on the Charles River. The vessel was only able to sustain flight for a few seconds at a time as weight was incorrectly distributed causing instability. Most of the weight was towards the stern causing the bow to excessively rise. Once in flight, repositioning oneself to balance out the weight led to increased flight times. Roll stability was also better than expected and the vessel was stable in level flight but would lose control and dive into the water during turns. Overall, the feasibility of homebuilt hydrofoils was successfully demonstrated, and the project was a success.

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