Design, Construction, and Testing of a Hydrofoil Rowing Shell

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ABSTRACT

This goal of this project was to develop a hydrofoil rowing craft. A set of hydrofoils was designed and built to attach to a conventional single-person crew shell. The foils were designed through a combination of numerical modeling and standard foil calculations. A spreadsheet was written to perform hydrofoil calculations and optimizations, accounting for a foil geometry, spray drag, junction drag, and surface effects. The foils were optimized for aspect ratio and planform area, and constructed out of carbon fiber using a hand layup with vacuum bagging technique. The foil performance matched the predictions of the spreadsheet over a range of speeds and angles of attack. When tests were conducted on the river, the shell foiled successfully with several different rowers of different heights and weights. By adjusting the angles of attack of the foils, the shell can be adjusted so that almost anyone can fly.

1. INTRODUCTION

The goal of this project was to design and build a hydrofoil single-person rowing shell. The shell should be able to achieve stable flight and should be able to go faster while in the flying condition than a conventional displacement shell could go with the same amount of power.
The project was broken into two distinct phases. The first phase was spent learning about hydrofoils, the problem at hand, and designing a set of foils for the hull. I wrote a foil design spreadsheet that calculates lift and drag for a foil and optimized a set of foils for the project. In the second phase I found a hull, tested it in the towing tank at the US Naval Academy, and constructed and tested the foils.

2. BACKGROUND

In 2009 a team at Yale University built a successful hydrofoil single-person rowing shell using a modern rowing shell and carbon fiber foils. They used a large T-foil in the stern, almost directly underneath the rower and a smaller T-foil at the bow for balance. Two struts attach the foils to the hull and hold the weight of the shell while it is flying. The struts are symmetrical foil sections, oriented vertically. The basic design and foil configuration of the Yale project was used as a starting point for this project. Figure 1 shows the basic T-foil configuration.

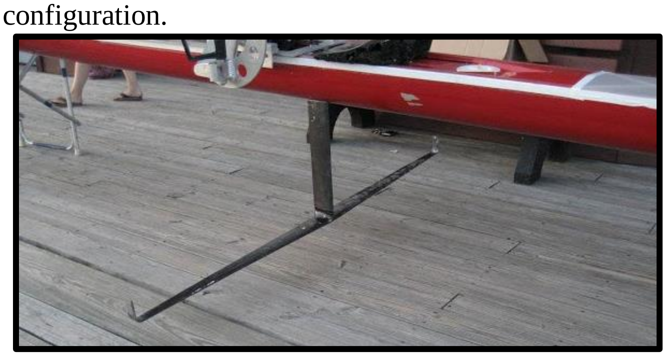


Figure 1: Picture of the Yale hydrofoil project, showing the main T-foil in the stern.

2.1 Problems and Approach

There are several characteristics of rowing that make creating a hydrofoil rowing shell a unique challenge.

2.1.1 Weight.

In order to lift the system out of the water, the lift generated by the foils needs to equal the weight of the system. This includes the hull, rower, oars, rigger system, and the struts. The hull used was a Cuchietti Single J9, borrowed locally from a private owner. It is designed for racing, with carbon fiber and honeycomb construction.

2.1.2 Pitching

When rowing, the rower typically faces aft in the boat. They sit on a sliding seat and tie their feet to the boat. As they bend their knees and slide aft, the oar blades sweep forward. The rower then pulls the blade powerfully through the water by straightening their legs, causing the seat to slide forward, and rotating their torso back towards the bow. Since the rower is by far the heaviest component in the system, this back-and-forth motion significantly changes the longitudinal center of gravity of the shell. This would make achieving stable flight nearly impossible because of the pitching moment induced on the shell by this motion. Figure 3 shows a conventional rowing rig. The rower's seat slides back and forth on the tracks while the rigger and feet are fixed in place.

Figure 3: Picture of a traditional rigger system for a single scull.

In order to combat the pitching problem, we adopted a sliding rigger system. In the modified system, the seat remains stationary and the rower's feet, along with the riggers, move fore and aft as the rower takes a stroke. This significantly decreases the pitching moment on the hull. Sliding riggers are a proven design, however they are seldom seen because they were banned from rowing competitions (both nationally and internationally) in the early 1980's. One of the many tasks of this project involved modifying two separate sliding seat rigger systems and creating one sliding rigger system to install in the hull. One rigger system that we purchased had a seat and set of tracks that were mounted to the hull. However, the rigger itself (the main piece that crosses the hull and holds the oars) was made out of aluminum. A different rigger made of carbon fiber was used instead to provide the lightest possible arrangement.

2.1.3 *Resistance*

Since the goal of the project is to use the foils to reduce resistance, the drag of the foils when the shell is flying needs to be less than the drag of the hull at the same speed. Rowing shells are specifically designed for the absolute minimum drag possible. The margin of drag between the condition of flying and operating in displacement mode will be very small. When the foils are attached to the hull, there will be significantly more resistance for all speeds until the shell starts to fly. This means that the rower needs to be able to provide enough power to overcome the additional resistance that occurs before the takeoff speed.

2.1.4 *Inconstant Speed:*

Sailboats and powerboats operate at a constant speed, which means that the lift the foils generate is constant. A crew shell varies in speed depending on where in the stroke the rower is. While the rower is pulling, the shell is going at nearly maximum speed. The maximum speed is achieved at the instant the oars leave the water and the shell slows down at a fairly constant rate over the "recovery" portion of the stroke, where the rower prepares to take another stroke. Since the rower's weight (or, in the case of a sliding rig system, the rig) is also moving toward the stern during the recovery, this further slows the boat down. The consequence of this variation in speed is that in order to fly consistently, the slowest portion of the stroke needs to be as fast as the design flying speed. This means that the "average speed" for the shell would need to be faster than the design flying speed for it to stay airborne.

3. DESIGN OF HYDROFOILS

A hydrofoil works by generating enough force from a lifting surface to lift the hull of a boat out of the water. The foils act on the same principles as airfoils on airplanes or gliders. One of my first steps in the project was to learn more about hydrofoils. I began by studying *Theory of Wing Sections* (Abbott and Von Doenhoff, 1949). This provided a basic knowledge of the principles of flight, lift and drag components of wings, and the effect of aspect ratio, which is the ratio of the span (length) of the wing to the chord. Figure 4 shows the main dimensions of a rectangular foil, looking down at the top. The planform area is the total area shown. Figure 5 shows the cross-section of a cambered foil, meaning the foil is not symmetrical around a straight line drawn from the leading edge to the trailing edge. A cambered foil produces more lift for a given angle of attack than a symmetrical foil.

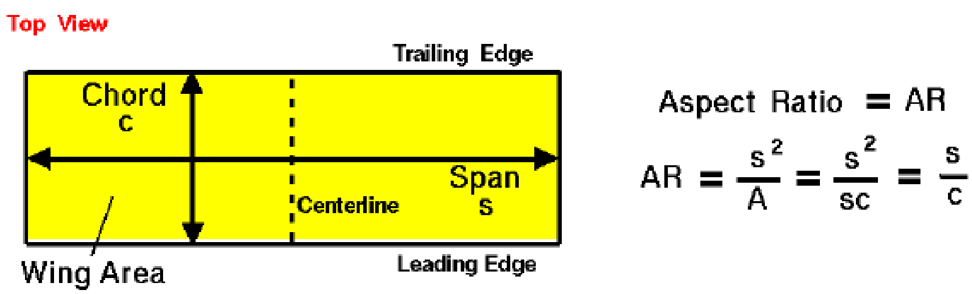


Figure 4: Diagram showing main foil dimensions

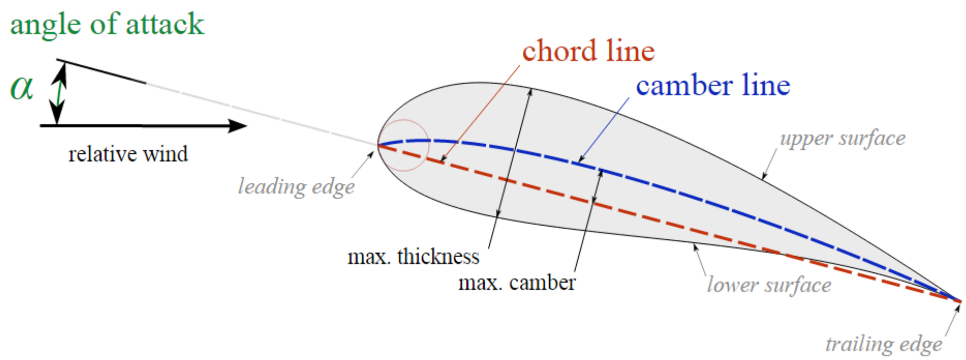


Figure 5: Cross-section of a typical cambered foil

3.1 Drag and Weight Budgets

The driving idea behind hydrofoil design is that of a drag budget and a weight budget. In order to fly, the weight of the whole system needs to equal the amount of lift produced by the foils. Since the lift generated is dependent on the speed of the shell, a design takeoff speed needed to be determined before the project could continue. Since I wanted to be able to row the shell, I used a GPS to determine how fast I could row in a single shell and based on the data collected from the tests determined that 11 ft/s was a realistic takeoff speed for me. The foils need to generate an amount of lift at 11 ft/s that is equal to the total of all of the components of the weight budget. The components of the weight budget include: the rower, the hull, the riggers, the oars, the foils and struts, and the seat. Initially I had to make estimates for the riggers and the foils and various components of the rig which were not yet assembled.

In order for flight to be beneficial, the drag of the system with the foils needs to be less than or equal to the system without the foils. The foils necessarily add drag to the hull when it is operating in displacement mode. However, the foils also create more drag as they move through the water faster, until the hull is lifted out of the water. The point immediately before takeoff is the point with the highest drag, which is where the drag budget is evaluated. The sources of drag in the drag budget include: hull pressure and friction drag, foil pressure and friction drag, strut pressure and friction drag, spray drag where the foils pierce the surface of the water, wave drag from the foils acting on the water surface, and junction drag where the foils and struts are joined together.

3.2 Foil Spreadsheet

From the basic principles found in Abbott and Von Doenhoff, I started to write an excel spreadsheet that would eventually be useful in designing foils for a specific task. Along with excel, I used the program Xfoil, which was written by Mark Drela at MIT.

In order to obtain two-dimensional foil performance data from Xfoil, the user must input both Reynold's number and section shape. For the section shape I initially selected an Eppler 195 section, a cambered foil section that is commonly used for hydrofoils due to its superior performance at low Reynolds numbers. The Reynolds number is found from the water temperature and density and the chord length of the foil section.

The Xfoil program outputs are drag and lift coefficients for a theoretical two-dimensional section shape. It uses numerical modeling to calculate the coefficients for a specified range of angles of attack.

In order to estimate the performance of a 3-dimensional foil, after the initial drag and life coefficients are found, they need to be adjusted for aspect ratio. A small aspect ratio results in a large loss of lift due to shedding of lift off of the tips of the wings. Lift is always lost at the tips of a wing, but the effect is proportionately smaller as the aspect ratio approaches infinity.

Once the user enters the data from Xfoil and the foil span and chord into the spreadsheet, it applies the aspect ratio correction to the coefficients. The resulting output is the data for a foil operating far below the surface of the water.

Because a foil generates lift by creating a pressure differential, it loses lift and increases in drag when operating near the surface of the water. If the pressure differential begins to act on the surface, it creates waves that negatively affect the performance of the foil. Because of this, a second correction was performed to account for the actual operating depth of the foil. In this case, the depth correction was estimated based on the method described in *Fluid-Dynamic Drag* (Hoerner, 1993).

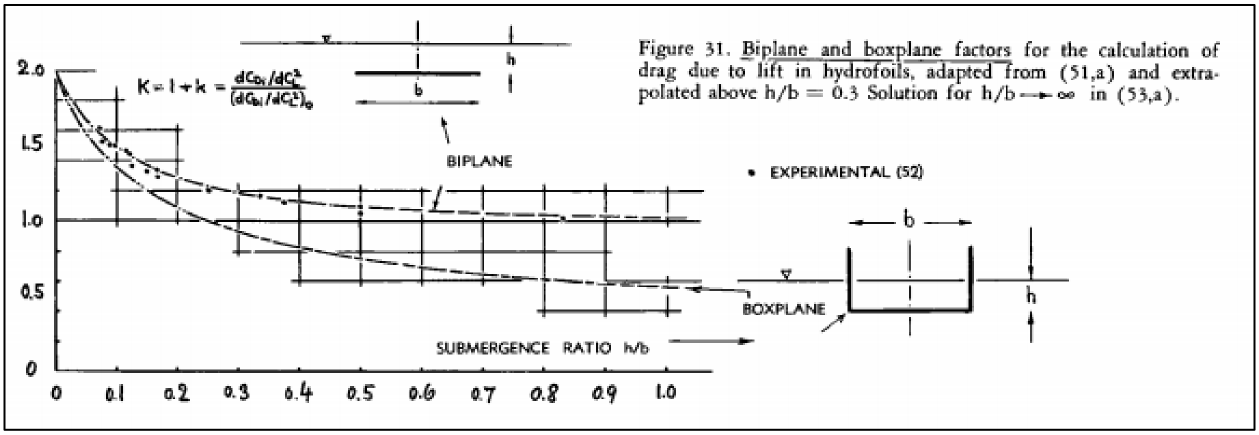


Figure 6: Hoerner's Drag plot for depth

Figure 6 shows a plot of the submergence function used in the spreadsheet. The biplane curve, which is the top curve, was used because it is closer to being accurate for a single foil supported by a middle strut. The x-axis shows h/b, which is the submergence of the foil divided by the span. The "K" factor, which is the y-axis, is a factor applied to the drag coefficient when the correction is made for aspect ratio.

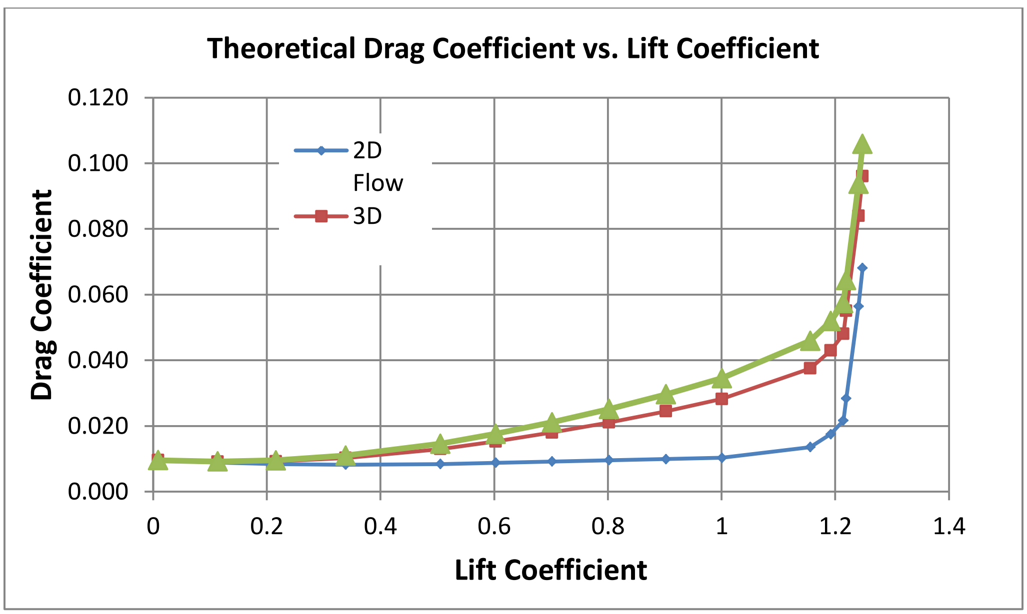


Figure 7: Adjustments to drag coefficient from 2D theoretical flow to 3D finitely submerged flow for the main foil.

Figure 7 shows the step-by-step analysis for the main foil. In Figure 7 drag coefficient is plotted versus lift coefficient for an Eppler 195 section. The blue line is for a foil with infinite aspect ratio, which is the data obtained from Xfoil. A correction for an aspect ratio of 17.8 is applied and the result is the red line, which assumes infinite submergence. Finally, the correction for 18 inches of submergence is applied and the result is the green line, which has the highest drag coefficient for a given lift coefficient of the three. Using a cubic spline macro in Excel, the angle of attack and speed can be entered into the spreadsheet and it calculates lift and drag for a given angle of attack. Using the goal seek function in Excel, angle of attack can be found from the speed and amount of lift required.

3.3 Struts

Because we chose to use a T-foil configuration, two vertical struts were required to hold the hull up from foils and the drag components of these struts must be accounted for. Since the struts are made from foil sections, the process for finding theoretical two-dimensional drag is the same as for the lifting foils. However, the strut experiences two sources of additional drag that need to be accounted for: spray drag and junction drag. "Spray drag" is drag that occurs because of the spray generated where the strut breaks the surface of the water. This drag is only present when the shell is in flying condition. Junction drag is a small amount of extra drag due to the joint between the strut and the lifting foil. The actual value of junction drag depends on the construction of the foil but is approximately estimated in the spreadsheet. Both of these sources of drag are estimated using methods described in *Fluid-Dynamic Drag* (Hoerner, 1993). Table 1 shows an example output table for the spreadsheet.

Table 1: Summary output table of the foil spreadsheet

Lift Outputs		
Total Lift	154.33	lbs
Rear Foil Lift	120.86	lbs
Forward Foil Lift	33.47	lbs

Drag		
Drag w/o foils	7.56	lbs
Drag while flying	6.48	lbs

3.4 Specific Design

After creating the tool to assist in the design of the lifting foils, the next step was to begin to apply the actual conditions of the situation. Based on the weight of the shell, the rower, and an estimated weight of the foils, riggers, and oars the total required lift was determined. The weight distribution was primarily driven by the structural properties of the hull. The hull is reinforced in the area where the rower sits, so the foil that is intended to carry the majority of the load is placed near the structural support. The forward foil needs to be placed where it balances the boat around the center of gravity. It was determined that the weight distribution should be approximately 75%-25% fore and aft.

Since the aft foil would be carrying 75% of the weight of the hull, it was designed first. The first round of the spreadsheet analysis was to determine the span and chord of the foil that would produce the required amount of lift (approx. 120 lbs) with the least amount of drag at 11 ft/s.

3.4.1 *Optimizations*.

In order to design a foil which would generate the required lift at the planned speed with the least amount of drag I optimized the foils for planform area, span, and angle of attack. The optimization conducted took the following steps:

1. Aspect ratio and lift were held constant, while planform area was systematically varied. The amount of drag generated was recorded for each planform area. This was repeated for six different aspect ratios between six and sixteen.
2. The planform area for each aspect ratio which resulted in the least amount of drag was noted.
3. The minimum drag at each aspect ratio was plotted. Also, the optimum area was plotted against minimum drag.

From this optimization, the area needed to generate 120 lbs of lift for any given aspect ratio was found.

3.4.2 *Structural Considerations*

An important element in any hydrofoil design is the structural analysis. Because hydrofoils are designed to be as light as possible, they are susceptible to breaking. Additionally, as the foil flies through the water the wingtips deflect, which causes the foil to shed lift. Because of this, a maximum deflection of 3 inches was determined to be the acceptable limit.

The structural analysis was performed by modeling one half of the lifting foil as a cantilever beam. The coefficient of lift was assumed to be constant along the length of the wing, so the load was assumed to have the same taper ratio as the chord length. For analysis, the load was broken down into stepped loads, which were applied to the wing as though the planform area was stepped as well. Simple beam equations provide the wingtip deflection and maximum stress in the wing. Figure 8 shows the deflection across one half of the main foil using the cantilever beam method of analysis.

The structural analysis determined that the highest aspect ratio the wing could withstand was 17.8.

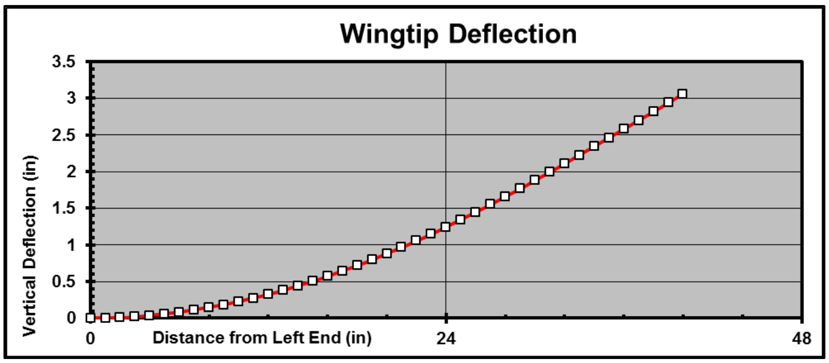


Figure 8: Plot showing modeled deflection across one half of the aft foil

3.4.3 *Foil Shape*

Three main foil shapes were considered when designing the foils: rectangular, tapered, and elliptical. Different foil shapes have different lift distributions across the span of the foil. Since discontinuities in the lift distribution are not possible, the lift distribution tapers off at the end of the foil. If it is perfectly rectangular, it will be underloaded at the tip because the lift tapers but the foil retains the full chord length all the way to the end. This is highly inefficient because the ends of the foil are producing proportionally more drag to lift than the middle of the foil.

An elliptical wing form is considered to have the most efficient lift to drag ratio because the lift distribution matches the planform area distribution, meaning that the foil is evenly loaded across the span. For a taper ratio of 1, meaning a perfectly triangular wing, the lift does not taper as fast as the planform area, meaning that the tips of the foil are actually overloaded.

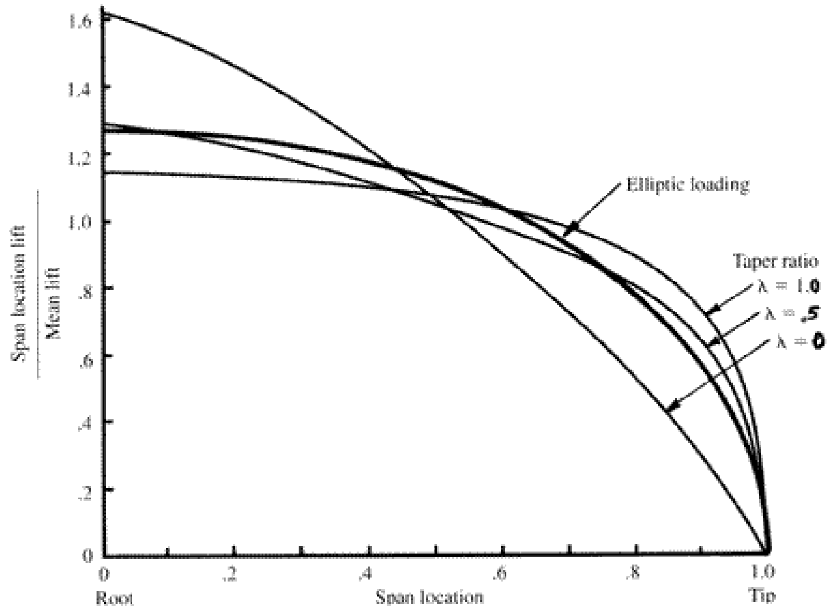


Figure 9: Typical lift distribution across different foil shapes

The plot shows that a taper ratio of 0.5 approximately follows an elliptical lift distribution. Since a foil with a taper ratio of 0.5 is far easier to construct than an elliptical foil, this is what I ultimately chose for the foil design. In order to construct an elliptical wing, elliptical sections of carbon fiber cloth would need to be cut and measured. With a tapered section, the lines to cut are straight and simple to draw and measure. Because straight strips of fabric are used to construct the foil, waste of fabric is also minimized. Figure 10 shows a cross section of the final design of the main foil, showing the taper ratio of 0.5 from the center to the tip of the foil. Figure 11 shows the top view of the final design for the main foil.

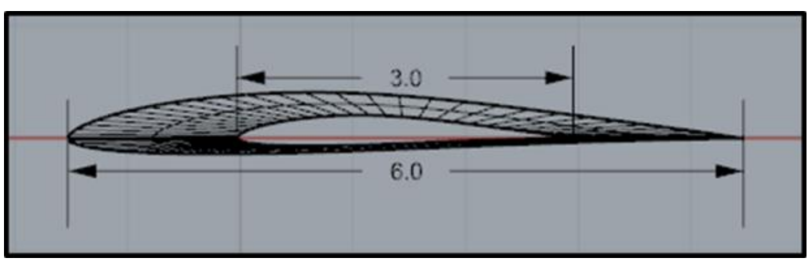


Figure 10: Cross-section of the final design, showing the cambered section shape and the taper from the middle to the tip.

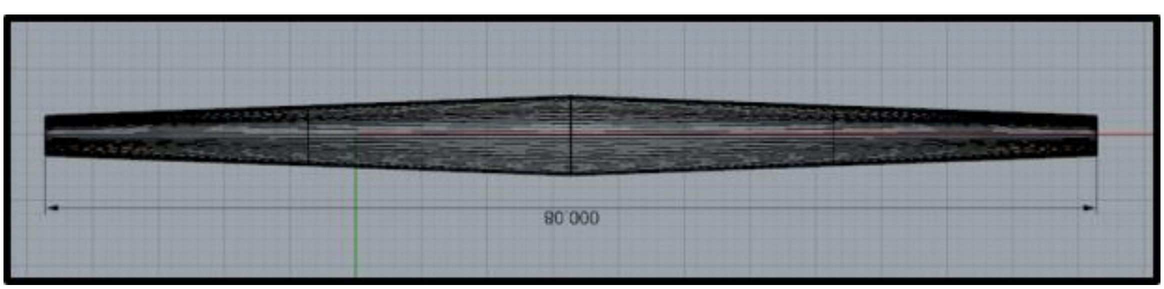


Figure 11: Top view of the main foil final design. Shows full 80-inch span.

4. CONSTRUCTION

The foils were constructed out of two different types of carbon fiber material using female molds. The outer two layers of cloth on the foils is 45-45 degree woven material. These layers give the foils strength in torsion. The remaining 10-12 layers are unidirectional material, with the fibers oriented running parallel with the span of the foil. These give the foil strength in bending. The foils were constructed one at a time. For the construction of the main foil, the individual layers for both halves were cut initially. After the molds were prepared, the foil layup was done for both halves simultaneously. To cure, the two halves of the foil were both sealed and placed under suction (vacuum-bagged) in order to remove excess resin to lighten the final product. When the pieces were cured, they were removed from the mold and then trimmed. Fiberglass cloth was used as a core, and the two halves of the foil were glued together using epoxy. The struts were constructed in the same manner.
For ease of construction, I decided to construct the smaller foil from the same mold as the aft foil. In order to keep the aspect ratio as high as possible, the middle section was cut out of the mold and the two ends were glued together. Using the spreadsheet, it was determined that the optimal span for the forward foil was 50 inches. The construction followed the same process as the main foil.

5. TESTING PROGRAM

All tests were conducted in the Hydromechanics Laboratory in Rickover Hall at the United States Naval Academy. The tank is outfitted with two towing carriages, a dual flap wavemaker and specialized equipment for measuring resistance, seakeeping and maneuvering characteristics of all types of marine vehicles and ocean platforms. The dimensions of the towing tank are: Length - 380 ft, Breadth - 26 ft, Depth- 16 feet.

5.1 Hull Testing.

The hull to be used was initially tested without the foils attached. The resistance of the hull by itself determines the drag requirements of the foils. If the foils have more resistance than the hull without the foils, then there is no resistance benefit to creating a hydrofoil craft. The tests required very simple instrumentation, as Figure 12 shows the setup of the testing rig. The shell was free to heave but constrained in all other directions of motion.
Resistance tests were conducted at three different displacements, at several speeds centered around the design takeoff speed. The four speeds tested were 9, 11, 13, and 15 ft/s. Figure 13 shows the results of the resistance tests on the bare hull. The data collected in these tests were used to complete the drag budget for the design of the foils and the EHP curve for the "conventional" crew shell.

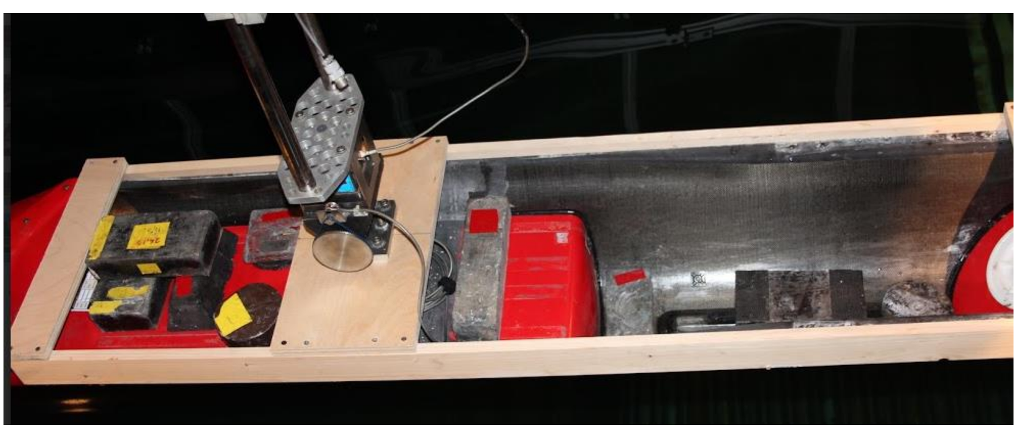


Figure 12: Test rig for the hull resistance tests. Resistance was measured using a 4-inch block gage.

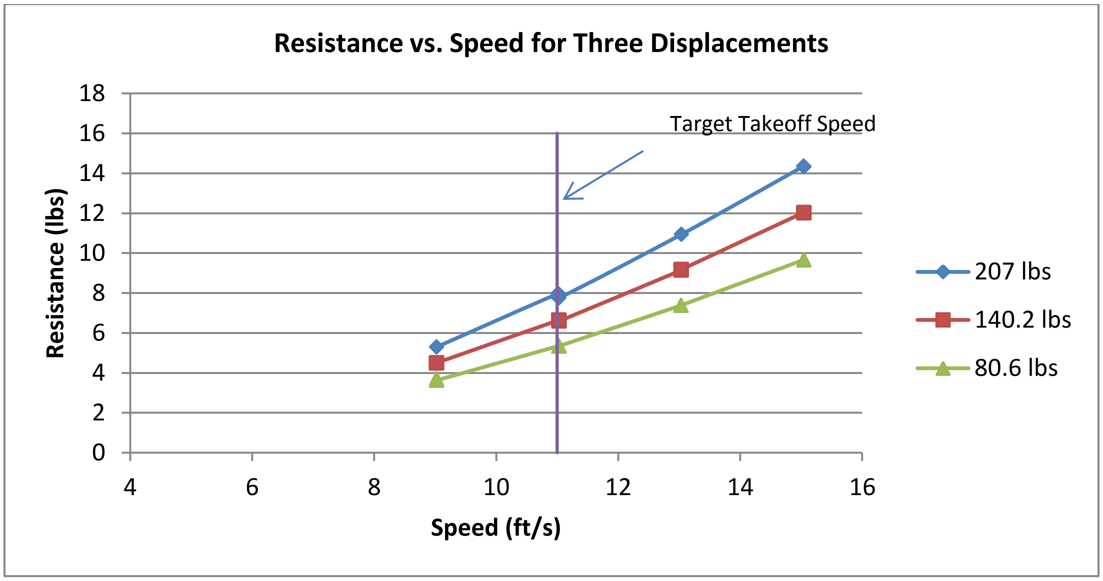
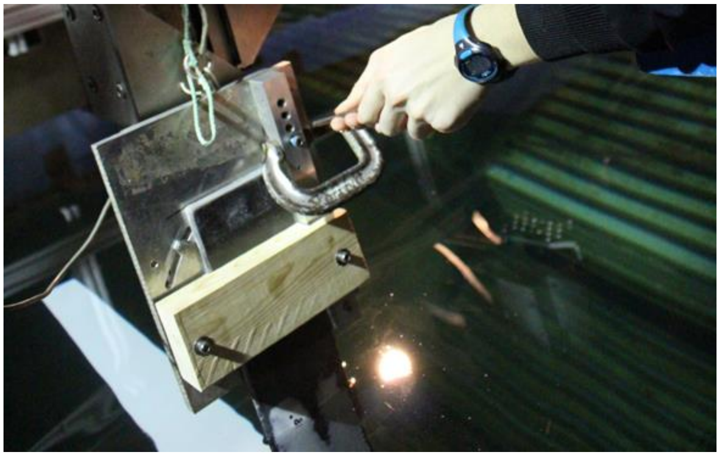


Figure 13: Results of the hull resistance tests, showing resistance vs. speed for three displacements.

5.2 Foil Testing



Figures 14 and 15: Towing configuration for the lift and drag tests done on the main foil (left). The bracket used to fix angle of attack is shown on the right.

The main purpose of conducting tests on the main foil were to compare the predictions of the spreadsheet to the performance of the actual foil and determine whether it was possible for the foil to generate enough lift to lift the crew shell out of the water. Lift and drag were measured at various speeds. Figure 14 shows the towing configuration for the tests.

In order to collect data two block gauges were attached to the foil to measure the lift and drag. In order to set and measure angle of attack, a special bracket was used. The bracket consisted of two metal plates which could rotate against each other. One plate had a sequence of holes drilled in it for various angles, and the two plates could be pinned together to set the angle of attack. Figure 15 shows the bracket with

the holes to adjust angle of attack. The foil could be raised and lowered using the apparatus of the towing carriage.
Both tests consisted of runs at velocities of 9 ft/s and 11 ft/s at varying angles of attack (-4 deg to +3 deg). In addition to changing the angle of attack, the foil was tested during the first test at submersion depths of 18 inches and 6 inches. During the second test, the foil was tested at 18 inches and 12 inches. Additionally, the strut was tested individually following the second test on the foil. The strut was tested at depths of 12 and 18 inches.

5.3 Testing Analysis

5.3.1 Struts.

The strut was tested at a range of velocities at 12 and 18 inch submersion depths. Theoretically the strut tested by itself should have pressure drag, which would be linear in relation to the submersion for a given speed, and spray drag, which would be a constant value for a given speed. Figure 16 below shows the indicated "spray drag" value for each velocity tested. It can be seen that clearly the value is almost negligible. There is almost an even spread across zero, and no value indicates that the spray drag is greater than 0.1 lbs.

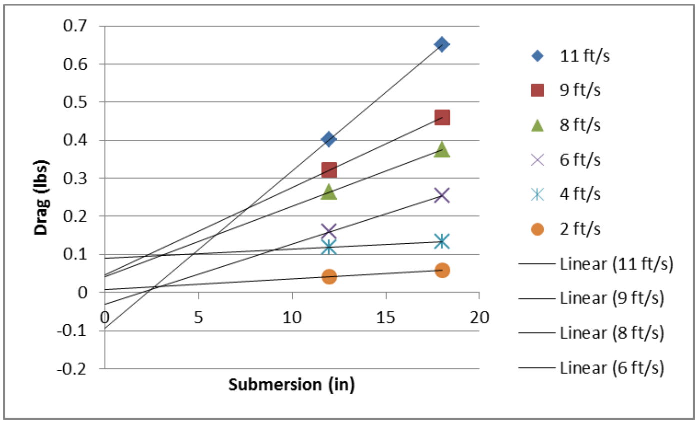


Figure 16: Drag vs. Submersion of the strut for a range of velocities.

The data is extrapolated back to 0 inches of submersion for each velocity. The line should intersect the y-axis at some value which is equal to the spray drag on the foil. However, the instrumentation was determined to not be sensitive enough to accurately measure such small amounts of drag and the spray drag was assumed to be negligible.

5.3.2 Foil Analysis

Although the foil performance is critical at only one speed and angle, the test data allowed for an analysis of the foil at a range of different conditions.
In order to evaluate the foil without the strut, the measured drag of the strut for the corresponding condition was subtracted from the total drag measured. The resultant drag is the drag of just the foil. Next, the coefficients of drag and lift were found using the area for just the foil ($2.5ft^2$).
When this analysis was performed on the foil and drag coefficient was plotted vs. lift coefficient, it was found that the foil matched or outperformed the predictions for the 18 inch submersion, which is the flying condition. Figure 17 shows the performance of the foil compared to the predictions. Drag coefficient is plotted versus lift coefficient, so the points that are lower on the plot indicate better performance.

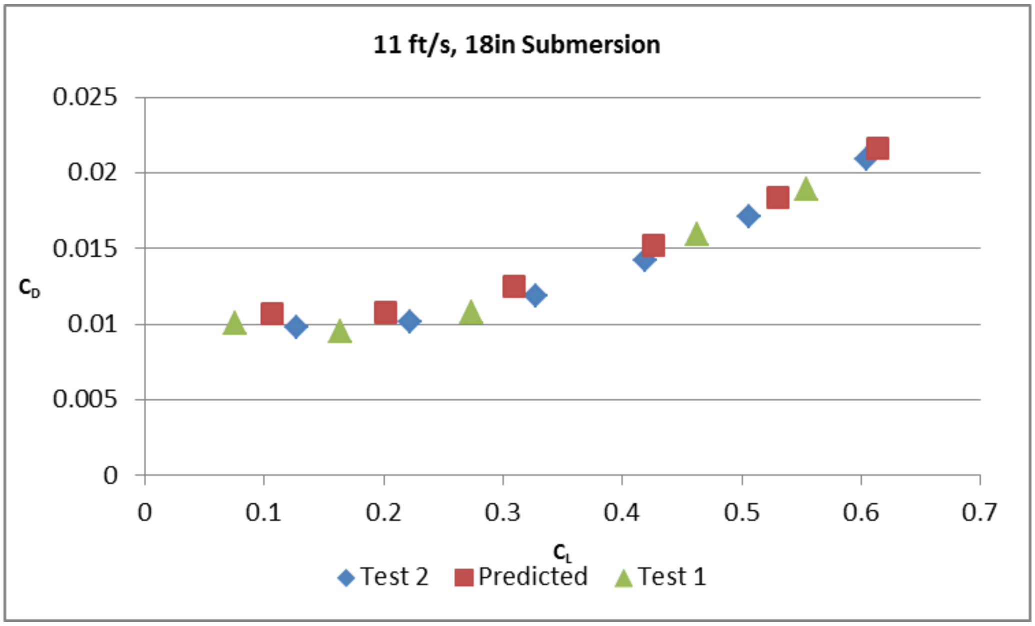


Figure 17: Comparison of foil performance to spreadsheet predictions

6. FLYING

For a final round of tests in the 380’ towing tank, the shell and foils together were tested free to heave and pitch, but constrained in roll. These were a series of qualitative tests to determine the best angles of attack to make the shell lift out of the water correctly. The shell was ballasted to 160 lbs placed at the approximate longitudinal center of gravity and run at 11 ft/s (the design takeoff speed).
The goal of these tests was to make the bow lift out of the water slightly before the stern. In this configuration, the bow lifting out of the water increases the angle of attack on the main foil, which causes it to generate slightly more lift. If the stern lifts out of the water before the bow, this drives the angle of attack in the bow down and makes it harder to generate lift on the forward foil.

Figure 18: The shell being tested in the river.

6.1 Results

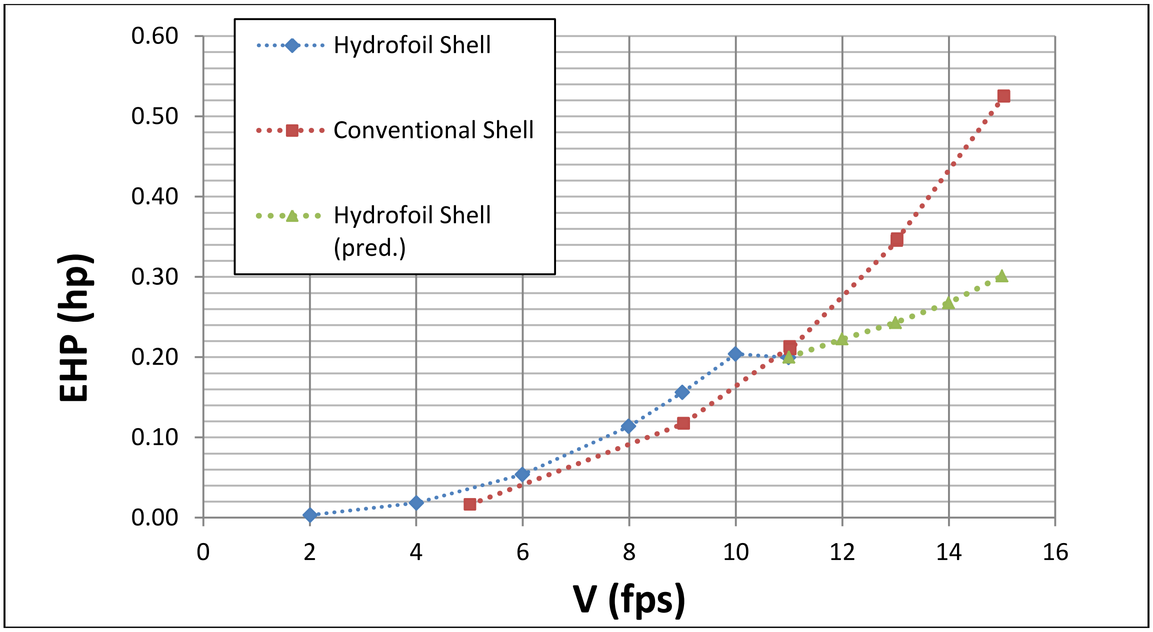


Figure 19: EHP vs. Speed for the conventional shell and the shell with hydrofoils.

Figure 19 shows the required power to reach various speeds for the crew shell. Power is shown in horsepower, and velocity is shown in ft/s. The red line represents the EHP curve for the shell without the foils, and is taken from the resistance tests done on the bare hull. The blue line shows the EHP curve for the hull with the foils attached. It can be seen that it requires more power to reach each speed when the foils are attached to the hull until the takeoff speed is reached. After takeoff, the green line represents the predicted value of resistance for the foils, provided the amount of lift generated stayed the same. These values are based on predictions from the spreadsheet.
The actual takeoff speed reached in the tests was 10 ft/s, which is slower than the initial design. This could be changed by adjusting the angle of attack on the foils. However, the foils do not begin to produce an advantage until the initial design takeoff speed of 11 ft/s.

7. RECOMMENDATIONS FOR FUTURE WORK

Although further testing needs to be done to determine exactly the speed at which the shell lifts out of the water, the project was ultimately a success. With a few modifications to the design to make it easier to row, it is likely that this is a human-powered hydrofoil can be flown by almost anyone.

The modifications to the shell to be made include making the struts shorter and moving the seat back. Moving the seat back will make it easier to row for anyone who is taller than 5’2”, although they still will not be able to reach full compression of the legs because of the placement of the bulkheads in the hull.

The struts need to be shorter because currently when the shell flies at full height it is too high off the water to row comfortably. The main foil will stay the same height in order to minimize surface effects and the forward foil will be shortened by 8 inches. This will bring the shell down to approximately 6 inches off the water.

8. ACKNOWLEDGEMENTS

This project would not have been possible without the help of:

Mr. William Beaver, MS, PE

Professor Gregory White

Mr. Thomas Price

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