EI-FOIL HYDROFOIL PROFILE ANALYSIS AND REAR MECHANISM DESIGN

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Abstract

From the 1990s Personal Watercrafts became a must have toy providing endless fun for all ages. Personal Watercrafts have since come a long way with design however still produce high emissions and noise therefore banning them in many places. This led to the development of the “Ei-Foil” which is an electric Personal Watercraft which glides on hydrofoils through the water. The Ei-Foil is eco-friendly producing very limited noise, zero emissions and brings a new form of riding to the Personal Watercraft world. However, due to riding on foils, the current design possesses stability issues which requires rider balancing to ride the watercraft. The first half of this thesis focuses on improving the hydrofoils design, thus leading into further stability improvements. This is analysed using computer aided technology and programs, to model the watercraft and analyse lift, drag, angles and flow fields. XFLR5 is used to model the foils to determine the best angle of attack when taking off, and when cruising. Due to finding differing angles of attack, the back foil on the Ei-Foil will be modified to be able to tilt which varies the angle of attack. The end aim is to allow zero rider experience to operate the Ei-Foil like a normal conventional Personal Watercraft, which will require further analysis in moving from a joystick system to an automatic system. The second half of this thesis proposes new concepts for the hydrofoil rear mechanism on the Ei-Foil. Addressing the problem of retracting foils when trailering the watercraft or coming into shallow water and adding aesthetics when the Ei-Foil develops into production. Concept designs for a folding external mechanism of the foils backwards, and a retraction winch system internal to the hull are both analysed and compared.

Letter of Transmittal

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19th October 2020

Professor Thomas Bräunl
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Dear Professor Bräunl

I am pleased to submit this thesis, entitled "Ei-Foil Hydrofoil Analysis and Rear Mechanism Design", as part of the requirement for the degree of Master of Professional Engineering.

Yours Sincerely

Layla Krishna
21713471

Acknowledgments

I would like to acknowledge the following people for the ongoing support and guidance throughout this thesis. First of all, Thomas Bräunl, for allowing me to work on the Ei-Foil project and the guidance, continuous meetings and feedback. To Eric Metrot and Piere-Louis Constant our project owners, for all the time and feedback in testing, software analysis and CAD drawings. To the REV team of both the Ei-Foil team and the Nuway bus team for always giving a helping hand, offering advice and always willing to help with special mention to Alishan Aziz and David Gregory in the electrics department. Lastly, I would like to thank my family and boyfriend, Joshua Parkes, for the ongoing support and motivation to always try my best and give my all to the project. The mentioned people above played an important role in the overall progress and completion of this thesis.

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Nomenclature

α	Angle of attack
COG	Centre of gravity
e-pwc	Electric Personal Watercraft
CAD	Computer-aided design
EV	Electric Vehicle
PWC	Personal Watercraft
REV	Renewable Energy Vehicle
UWA	University of Western Australia
Cm	Coefficient of moment
Cl	Coefficient of lift
Cd	Coefficient of drag
Cl/Cd	Coefficient of lift to drag ratio

1 Introduction

From motorbikes in 1950s personal watercrafts (PWC's) took fun from land to sea and became a must-have toy in 1990s [1, 2]. PWC's are vessels using an "inboard motor powering as a water jet pump" to propel the vessel, in which operators can sit, stand or kneel. The smaller size and lower overall cost of PWC's attracted water-loving families. Having ability to navigate shallow waters with ease, dock on the beach, pull tubes, easily trailering, launching with just one person and can cruise or reach high race speeds [3, 4]. PWC's have since come a long way in terms of stability, performance and reliability. With many types such as light recreation, towing, luxury and performance, PWC usage continues to grow in the modern world [2, 5]. However, due to the noise generated and high emissions, PWC's are banned in many places [6].

In the vehicle scene, the automotive industry is moving the trend to electric vehicles (EV) from gasoline-powered vehicles with an increase of 63% of EV's deployed around the world in 2018 compared to the previous year, displayed in Figure 1 [7]. With increased research, innovation and funding the benefits of EV's will soon outweigh the disadvantages of shorter travelling distances, battery replacements and expensive initial costs [8]. The advantages include; low running costs (charging vs fuelling), low maintenance (less moving parts) and huge environmental benefit (zero emissions and energy efficiency) [8, 9]. The boating industry responded creating various electric boats including PWC electric models such as Gratis X1 and Taiga Orca [10, 11]. The University of Western Australia (UWA) through the Renewable Vehicle Project (REV) have successfully converted a 2008 Sea-doo to a fully electric PWC (e-PWC) named the "REVski". Powered by a 3 phase induction electric motor, the REVski is Australia's first e-PWC [11, 12]. Adding the benefits of EV's, the REVski eliminated PWC's noise and pollution problem.

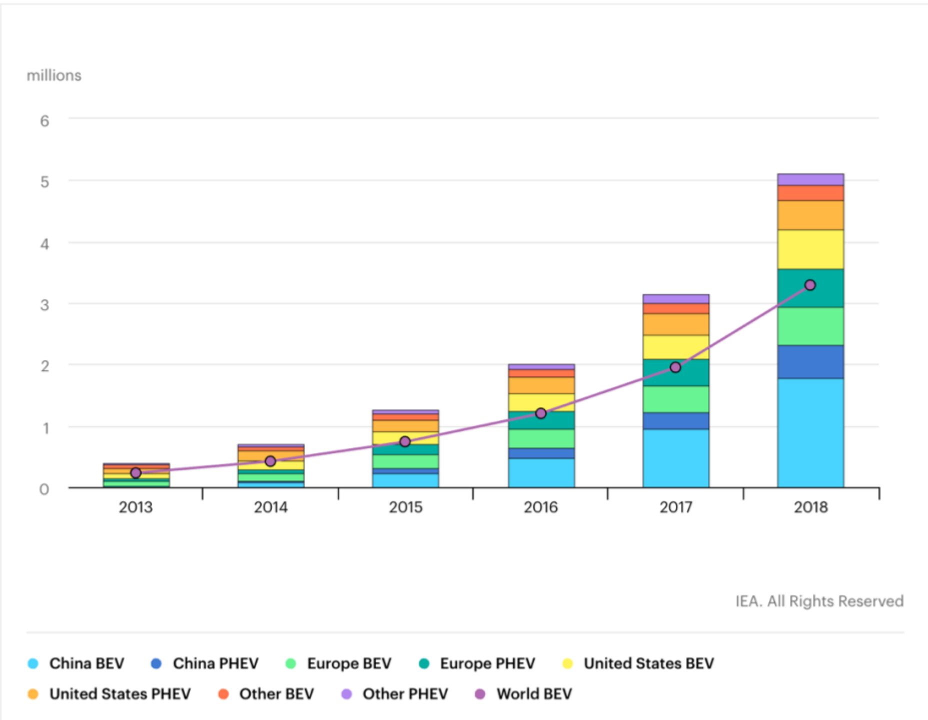


Figure 1: EV growth around the world [7]

Promising results from the Revski lead to the “Ei-Foil”, with the REV team in 2019, sponsored by Galaxy Resources and partnered with Electro.Aero, developing the world’s first electric hydrofoil PWC, shown in Figure 2 and Figure 3. A hydrofoil is a “foil or wing underwater used to lift the boat’s hull until it is totally outside the water”, significantly reducing drag [13]. Making the Ei-Foil eco-friendlier due to being more energy efficient and a much smoother ride brings a new form of riding to the PWC world [14]. Although, the Ei-Foil is still in development stages and has many aspects to research and perfect. Therefore, this project aims at improving the design by computer-aided technology to provide maximum energy efficiency while improving rider experience.

Figure 2: The Ei-Foil testing in water [14]

Figure 3: The Ei-Foil model

2 Problem Statement

Stability on modern PWC’s is controlled by hull shape. The surfboard modification to the Ei-Foil for weight reduction of the hull provides minimum flotation for initial stability, once on hydrofoils stability greatly decreases. This requires rider experience of great balance while on the foils with adjusting, by joystick, the ailerons attached on the back foil. When trying to turn or ride with 2 people, the balancing act becomes harder. The final aim for the Ei-Foil is to make riding the same as any conventional PWC, requiring no experience with no difficulty.

Therefore, the first part of this research project is to focus on improving and perfecting the hydrofoils design, to lead to further stability improvements in future projects. Based on the current designed foils, the profiles will be modelled in XFLR5, a foil software analysis program. The intent is to maximise stability by looking at lift, drag and angles of foil profiles before further adjustments are made to other components.

Due to the hydrofoils seen underneath in Figure 3, the Ei-Foil poses difficulty when launching from the trailer. The front foil is retracted up in the hull. However, the back foil is mounted onto an external mechanism with the motors, which adds extra length to the PWC shown in Figure 4 and Figure 5. It is desirable to have the back hydrofoil sit underneath the hull like the front to minimise Ei-Foil length. Due to watertight restrictions proving difficult, the start-up model placed the foil on an external mechanism which includes rudder steering. The second part of this project is to redesign the external mechanism ensuring the back foil sits underneath the hull, and the mechanism is fixed (no movement from steering like current). Hence, making launching easier.

Figure 4: Back hydrofoil mechanism view from behind

Figure 5: Back hydrofoil mechanism view from side

3 Contributions

The contributions from this thesis on the Ei-Foil varied over several different aspects. Extensive modelling and analysis were undertaken on XFLR5 for the hydrofoil profile analysis. For the second half of this thesis, computer-aided design (CAD) models were produced of the rear mechanism designs, requiring measurements from the foils. Many smaller tasks were accomplished to get the Ei-Foil running. Complete rewiring of the Ei-Foil eliminated noise in the cabling. The control box was moved to inside the hull to remove waterproofing issues. Some trial runs were conducted, requiring trailering of the Ei-Foil to and from launching points, and providing a support vehicle of my own PWC. Testing of the old electric PWC was carried out, requiring a skipper's ticket and knowledge to control the PWC. Overall all contributions were made to get the Ei-Foil in working condition to allow for the thesis improvements to be ready for implementation.

4 Literature Review

The literature below firstly reviews hydrofoil analysis and secondly the rear hydrofoil attachment mechanism. Hydrofoil analysis details the mathematical explanation behind how foils work, the different design aspects, and how the foils are analysed for optimisation and stability. Hydrofoil back attachment mechanism reviews different mounts to attach the back hydrofoil underneath the hull ensuring a watertight design and reviews the need to fix the rear assembly to allow no movement.

4.1 Hydrofoil Profile Analysis

Hydrofoils increase energy efficiency by lifting the hull out the water. The shape of hydrofoils are designed to allow flow to be deflected downward producing an upward force on the foil explained by Newtons Third Law of Motion [15]. Further explanation of how foils work, and design requirements are reviewed below.

4.1.1 Bernoulli's Equation

$$P_0 = P_1 + \frac{1}{2}\rho V_1^2 + \rho g y_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g y_2$$

P_0	Stagnation pressure	[Pa]
P	Pressure	[Pa]
ρ	Density	[kg/m^3]
V	Velocity	[m/s]
g	Gravity constant	[m/s^2]
y	Height	[m]

Bernoulli's equation is used to explain foil lift. Due to the small height difference in the foil, we can neglect this term, therefore left with pressure and velocity terms. Due to the increase in speed, there is a pressure drop and formation of vortices at the end of the foil. These are overcome by a counterclockwise moment at the trailing edge resulting in a higher flow speed above the hydrofoil compared to underneath. Hence with the lower velocity underneath the foil, there would be high pressure. This difference in velocity produces the force (Force = pressure x area) for the hydrofoil lift [16, 17].

4.1.2 Angle of Attack

The angle of attack of a foil (α) is defined as the angle the wing is pitched up [18]. By positioning the foil at an optimised angle, the lift to drag ratio can be maximised, diagrammed in Figure 6. Generally, with a small α (up to 4 degrees) the lift increases rapidly while drag only increases at a small rate. After 15 degrees stall can occur, which needs to be avoided. The most efficient angles are between 3 and 4 degrees [16]. However, α is affected by the type of flow i.e. laminar to turbulent, and the profile of the hydrofoil. A flexible hydrofoil undergoes slight deformation which changes the difference in pressure further towards the leading edge of the hydrofoil increasing the effective α [19]. Although, viscous effects move the difference of pressure more central and cause more large-scale separation of the flow, needing a higher α to overcome hence causing stall [19]. A limiting factor is also at high α's cavitation, "the formation of cavities on surface of low pressure", can occur [20]. Due to the complications of installing a mechanism to control α, this project will consider a foil attached at fixed α. In the analysis, α will be varied to find the optimal fixed angle to ensure maximum lift to drag ratio.

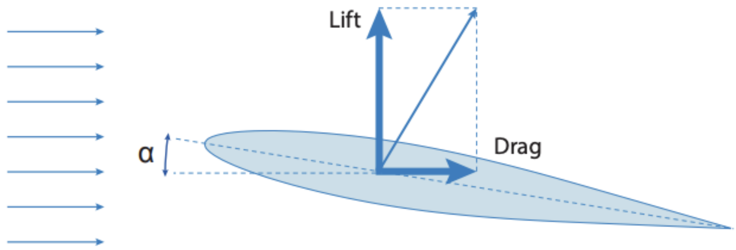


Figure 6: Lift and drag forces with angle of attack [21]

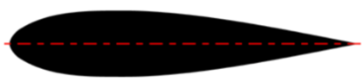
4.1.3 Hydrofoil Design

The design of hydrofoils can be modified in many different ways. First starting with choosing the best profile depending on desired outputs. Next, considering what type and shape of foil is to be used and in what configuration depending on the vessel's weight distribution and the location of foils.

4.1.3.1 Aerofoil Profiles

Aerofoils have many different profiles that can be modified depending on the requirements of the foil. Table 1 outlines some of the generalised aerofoil profiles with key attributes of each and Figure 7 is a diagram of key aerofoil parameters used. When choosing aerofoil designs, it is important to calculate the Reynolds number to validate the analysis [22]. Analysis using XFLR5 is undertaken on different profiles to determine optimised α corresponding to maximum lift/drag ratio as explained further in section 4.1.4.

Table 1: Foil profile benefits table [23-26]

Categories	Foil	Attribute
Symmetrical		Used for precision and avoiding cavitation. No lift at zero angle of attack therefore a stabiliser is traditionally used. Generally used for aerobatic planes.
Semi-Symmetrical		High lift to drag ratio even at small angles, having more lift than symmetrical but less than flat-bottom. Used in sailplanes due to needing to glide well and quickly climb.
Flat-bottom		Easy to build, generate high lift but also high drag. Extremely speed sensitive. Modified flat-bottom aerofoils are used when slow flight or high lift is required for compromise of high drag.

Under-cambered		Generates high lift at low angles of attack at minimum flow velocity (slow speed) due to efficiency of deflecting flow down. However hard to build.
Reflexed		Provides stability (self-stabilisation) due to trailing edge upwards but sacrifices lift. The trailing edge should only be slight, as too much reflex can send planes in a loop.

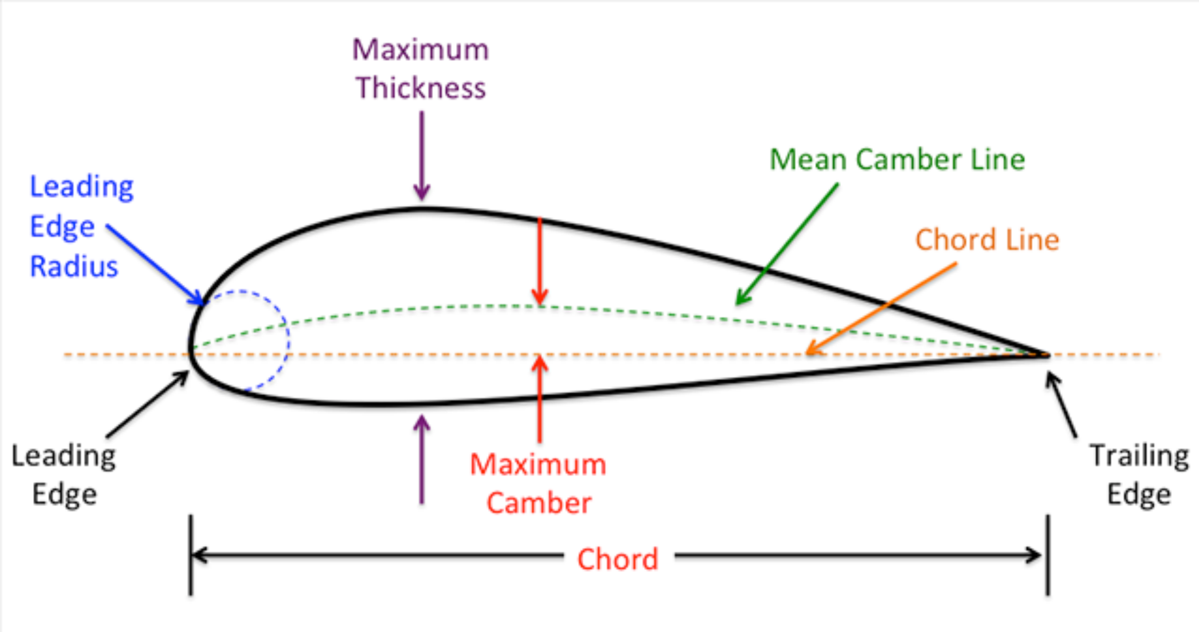


Figure 7: Aerofoil diagram [27]

4.1.3.2 Hydrofoil Types

Hydrofoils can be characterised into two types; fully submerged and surface-piercing foils in Figure 8. Submerged foils, usually "T" shape, remain wholly in the water whereas surface piercing foils, usually in a "U" or "V" shape, partially rise above the water [28]. Fully submerged foils are used on the "Boeing PMH" a hydrofoil US navy ship and "Boeing 929" a 250passenger carrying ferry in Japan [29]. Similarly, surface piercing foils were used for a Canadian navy ship "Bras d'or" and a 200passenger carrying ferry "Rodriques RHS160" in Italy [21]. Fully submerged foils are more stable and more comfortable to the riders in the aspect of reacting to wave effects [30]. Although control systems are required to maintain a constant height. Contrary with surface piercing hydrofoils the foil itself is fairly stable in pitch, heave and roll [21]. A deeper central hydrofoil submergence will generally produce higher lift [31]. The start-up Ei-Foil model uses a fully submerged hydrofoil, with advantages of stability and higher lift from deepness, as well as a major advantage of trailering. Hence the fully submerged foil will be analysed.

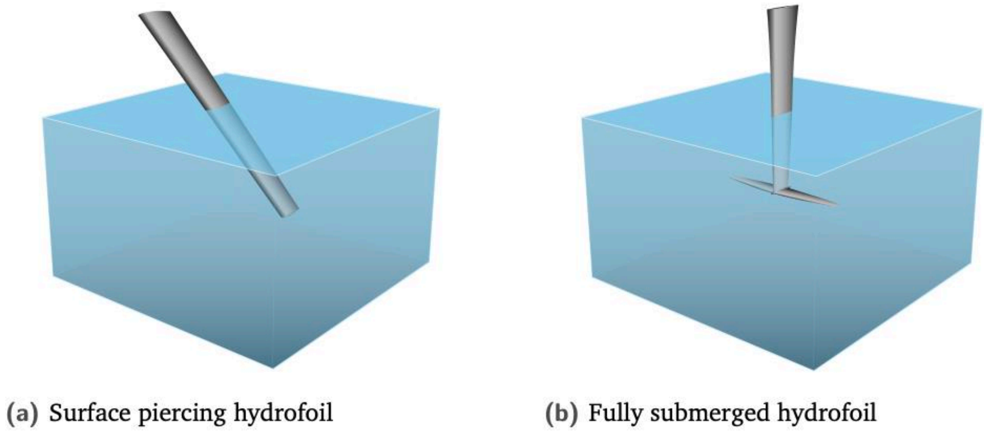


Figure 8: Hydrofoil types [21]

4.1.3.3 Hydrofoil Shapes

Typically, there are three hydrofoil shapes; T foil, V foil and Ladder foil (L foil if no levels) shown in Figure 9 [24]. The main foils being T and V. However, L shape hydrofoils are used on high-end record-breaking sailing yachts due to the need to overcome the sideward force from the sails [21]. Due to the T foil nature, the height and lift of the foil have to be altered either using the incidence of the foil (α discussed in section 4.1.2) or a trailing edge flap (camber control). Contrary the V foil reaches an equilibrium lift height once at speed automatically. The T foil has the lowest drag at starting speeds and increases with speed, whereas the V foil stays at a constant drag coefficient although higher than T at lower velocities [32]. The Ei-Foil currently has a T shape foil, chosen due to the difficulties faced of trailering the PWC. For the purpose of this analysis, the hydrofoil will be kept at a T shape.

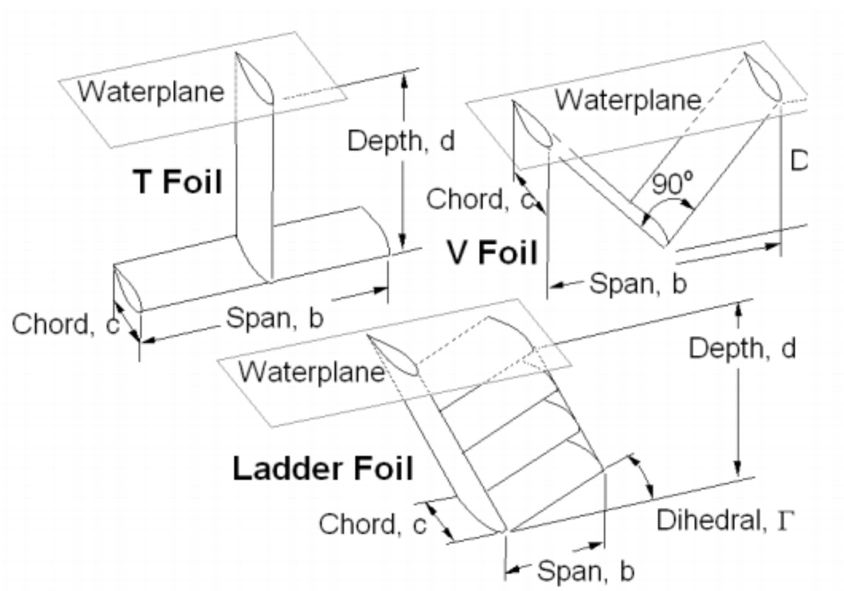
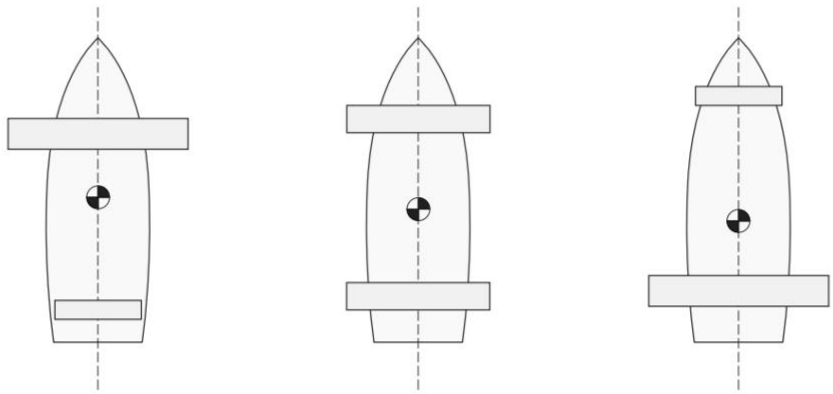


Figure 9: Hydrofoil shapes [32]

4.1.3.4 Hydrofoil Configurations

There are three main configurations of hydrofoils; classic, tandem and canard displayed in Figure 10. These configurations can affect the lift coefficients of the foils. The weight of the boat is supported mainly by the front wing in the classic configuration, whereas canard is opposite. In Tandem configuration the weight is evenly distributed between both the front and back foils [21]. Due to time restraints and the current used configuration, the tandem configuration will continue the analysis of the hydrofoils.



(a) Plane / classic (b) Tandem (c) Canard

Figure 10: Hydrofoil configurations longitudinal [21]

4.1.4 Foil Profile Modelling

The optimisation profile for the Ei-Foil hydrofoils will be modelled using XFLR5. The foil point profiles are extracted from Airfoiltools.com database and modified to suit. Currently, the Ei-Foil's main front wing is an Aquila9.3 (modified flat bottom foil) and the back wing is an Eppler836 (symmetrical foil) shown in Figure 11 and Figure 12. XFLR5 uses Reynolds number, Mach number and Ncrit value to analyse a profile. XFLR5 provides a streamlined analysis for profiling the foil into a wing and will be used for the main analysis.

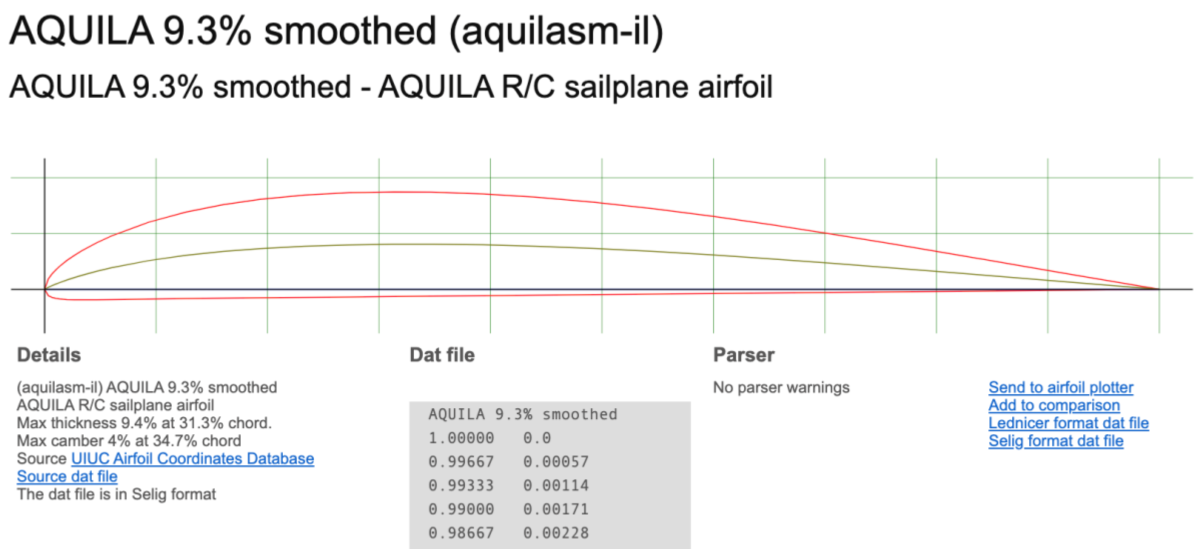


Figure 11: Ei-Foil Aquila 9.3 hydrofoil profile [33]

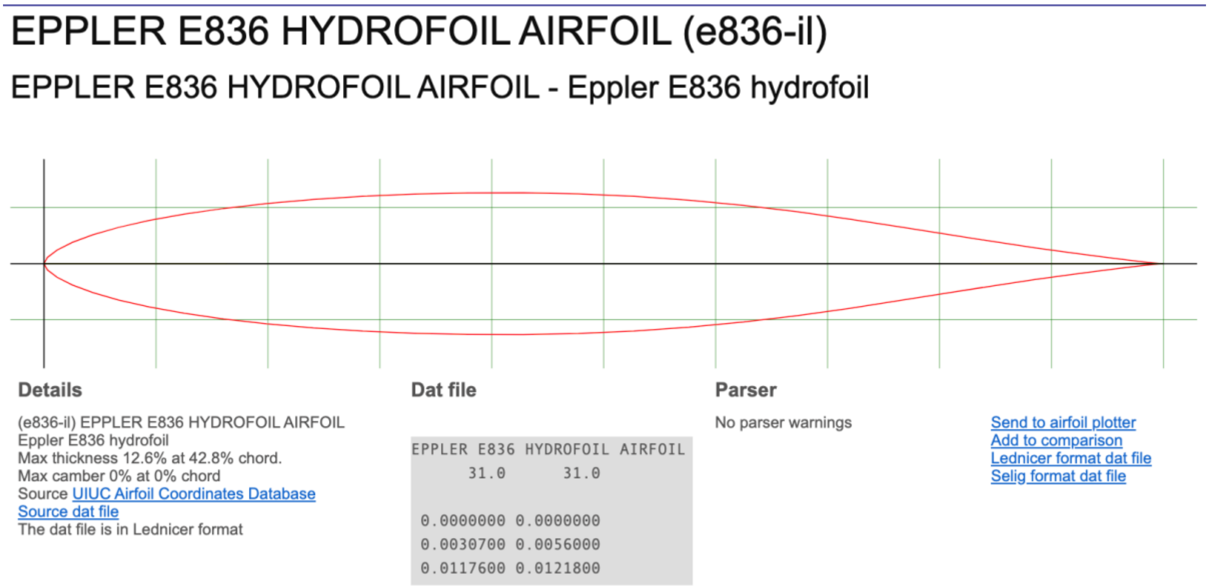


Figure 12: Ei-Foil Eppler 836 hydrofoil profile [33]

4.1.4.1 Reynolds Number

$$Re = \frac{\rho v l}{\mu} = \frac{v l}{\nu}$$

v	Velocity of the fluid	[m/s]	13
l	Chord length	[m]	0.148 (back), 0.19 (front)
ρ	Density of fluid	[kg/m^3]	997
μ	Dynamic viscosity of fluid	[kg/m/s]	8.90×10^{-4}
ν	Kinematic viscosity of fluid	[m^2/s]	1.0035×10^{-6} (at 20 °C)

The Reynolds number is the ratio of inertial forces to viscous forces. The calculated current back wing Reynolds number is 1,917,289 and front wing is 2,461,385. Indicating a turbulent flow [34].

4.1.4.2 Mach Number

$$M = \frac{u}{c}$$

u	Local velocity	[m/s]	13
c	Speed of sound through medium	[m]	1531 (seawater)

The Mach number is the ratio of object velocity to the speed of sound. The calculated Mach number for the Ei-Foil is 0.0084, indicating subsonic flow [35].

4.1.4.3 Ncrit Value

The Ncrit value describes the transitional boundary layer behaviour. The lower Ncrit values represent high turbulence, from 5 and below. In a typical analysis, an Ncrit value of 9 is used therefore for the purpose of this project, Ncrit = 9 [36].

4.1.4.4 Three Foil Profiles

The desired attributes of the Ei-Foil foils are:

- High lift to drag ratio at small α
- Delayed and predictable stall behaviour at high α
- Predictable behaviour at Reynolds numbers between 1,500,000 to 3,000,000
- Have an easy to manufacture profile

For this project, the Eppler836 and Aquila9.3 will continuously be analysed by changing the length of wings, chord width, angles of attack, differing configurations and mast placements. Due to the need to increase stability, the NACA 25112 profile (Figure 13) is analysed for comparison due to its slight reflex profile with an increased camber at the trailing edge [37]. The reflexed camber has shown to reduce pitching nose down moments, allowing static stability. However, at low angles of attack, the effect of reduced lift should not be too significant [38].

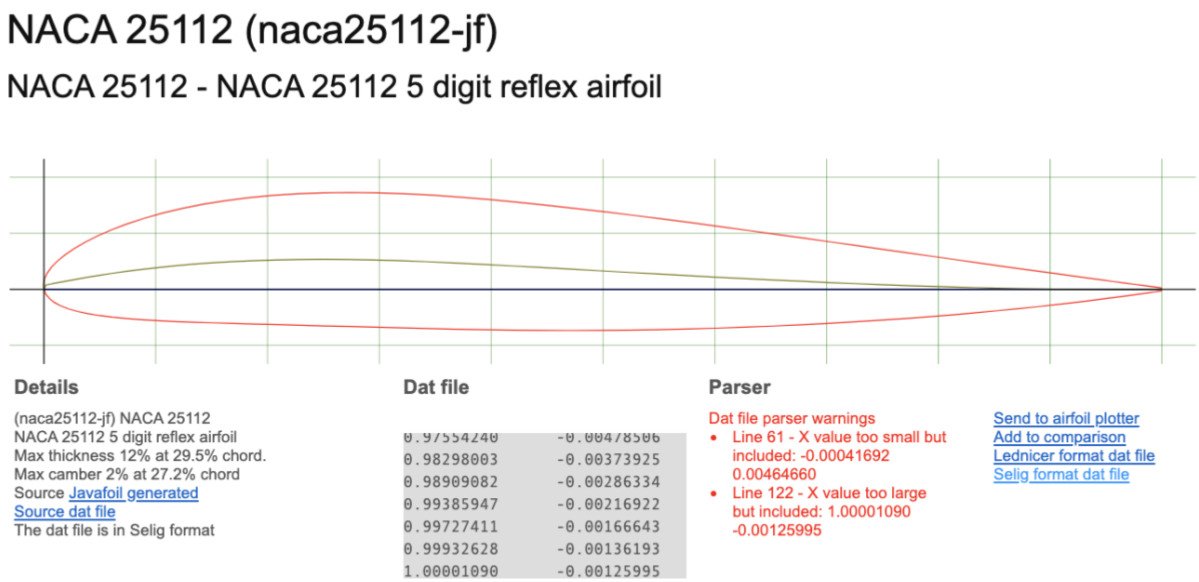


Figure 13: NACA 25112 foil profile [33]

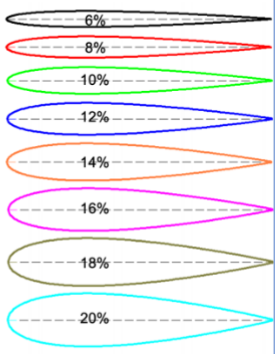
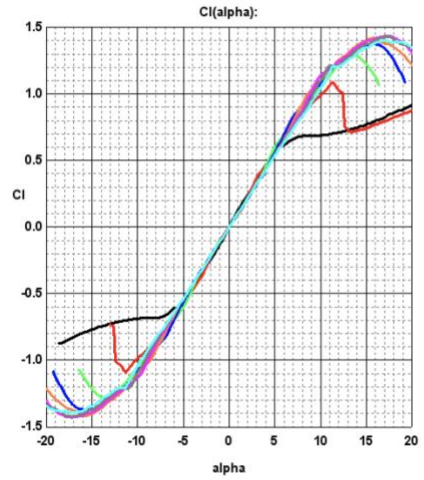
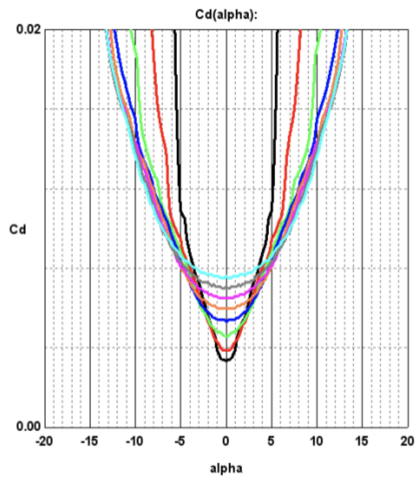
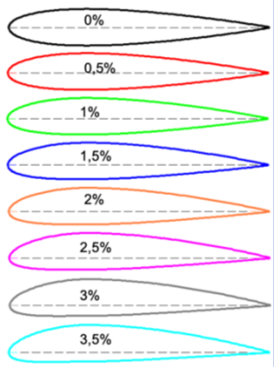
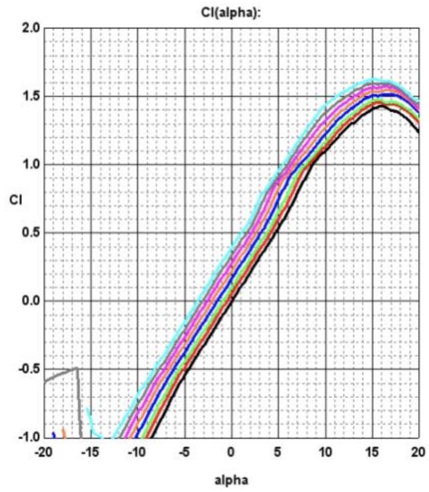
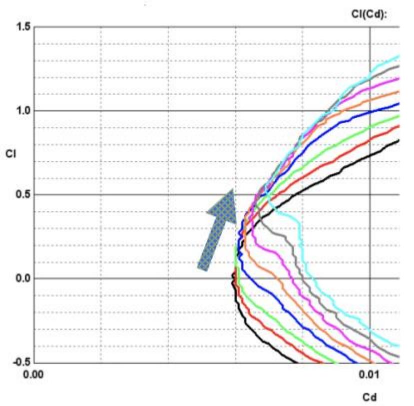
4.1.4.5 Analysing CL, Cd and Cm

XFLR5 allows the analysis of foils by producing graphs. The main graphs used are coefficients of lift (Cl), drag (Cd) and moment (Cm). At CL max stall sets in therefore ensure α is below this point [21]. A negative slope on the Cm graph indicates the foil will be stable, with a steeper slope indicating the strength of the stabilizing force. Iterations to find the optimal angle of attack for the Ei-Foil foils is to find Cm at 0, check that Cl>0 and optimise for a high CL/CD vs α curve [39].

4.1.4.6 Effect of Parameters on Coefficients

Table 2 shows how changing the thickness and camber of the foils can affect lift and drag. This project will analyse the different effects of thickness and camber on all three foils using XFLR5.

Table 2: Thickness and Camber affecting lift and drag coefficients modelled in XFLR5

	Lift	Drag
	Thickness	
		
	Camber	
		

4.1.5 CFD Stability Analysis using ANSYS

There are 6 degrees of freedom on a boat shown in Figure 14. Typically, a boat's hull will control the hydrostatic forces of heave, roll, pitch and yaw but due to the Ei-Foil hydrofoils, these forces need to be controlled separately [24]. Surge is controlled through motors. A canted foil can be used to control sway. Roll can be controlled by two adjustable cambers. Heave is controlled by the submerged foil naturally balancing but if unachievable, adjustable cambers can help. Pitch stability is controlled by the configurations of the foils on the vessel. Yaw stability requires a rudder [40, 41]. For the purpose of this project, the hydrofoils are analysed in XFLR5, however full stability analysis is desired in ANSYS Fluent to confirm maximum stability. Therefore, only the hydrofoil profiles will be analysed for streamlines of drag, lift and stability at current with future analysis to be undertaken in ANSYS. ANSYS will validate coefficients of lift and drag, the forces on the foils and drag forces. Three different angles of attack will also be modelled in ANSYS to compare results [42].

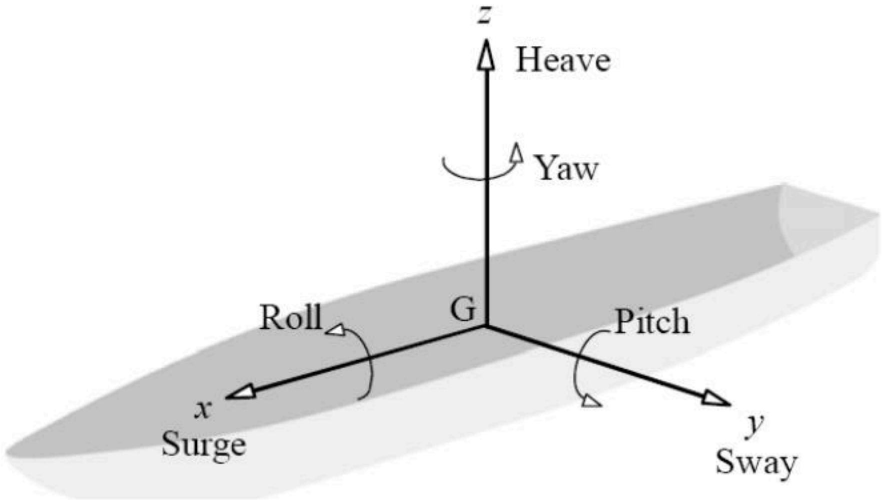


Figure 14: Degrees of freedom of boat [40]

4.2 Hydrofoil Attachment Mechanism

4.2.1 Rear Assembly Fixed

PWC's steer by moving the whole rudder propulsion system, which on the Ei-Foil this same system was kept so when steering the whole back system moves. However, causing major balance issues due to the PWC foils. A fixed strut steering control only swivels part of the foil shown in part 50 in Figure 15. This maintains balance and structure stability of the main foil masts [43]. A control system with the use of gyroscopes and accelerometers is used by The Boeing Company to automatically control trailing edge flaps (part 18 in Figure 15) in the navy and passenger hydrofoil crafts. Traditionally used for pitch and roll, they can be used in combination with a rudder (part 50) to bank the ship on the roll axis to turn [44]. Figure 16 shows another configuration in which a larger rudder moves, also stating the problem of difference in height from COG of the boat to rudder, causing more force required for steering than having the hull on the water, proposing that front foils be used for steering as well [45]. These designs from patents, back up research of fixing hydrofoil struts and controlling steering differently, therefore evident that the back hydrofoil should be non-movable (turning) and should be updated to fix this. Future analysis will build on the fixation by modifying the steering.

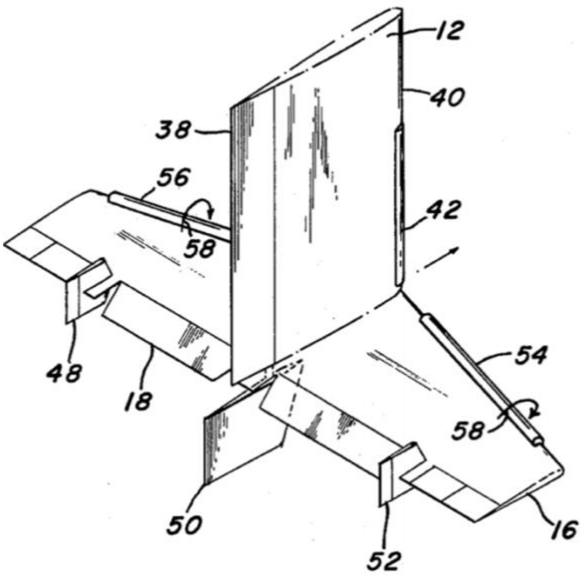


Figure 15: Hydrofoil fixed strut steering control [43]

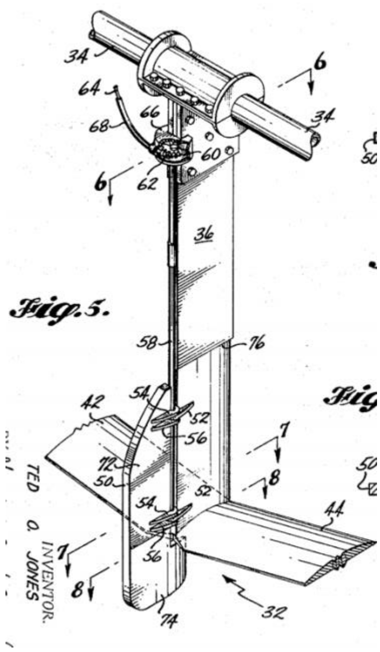


Figure 16: Rudder control on Surface Pierced Hydrofoil [45]

4.2.2 Rear Mechanism Foil Attachment Design

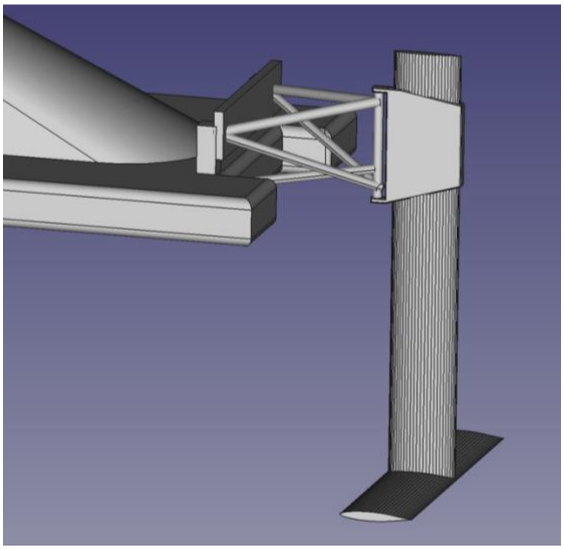


Figure 17: Simplified Basic CAD model of the Ei-Foil Rear

Figure 17 displays a simplified constructed CAD model of the current rear mechanism. With the literature review from section 4.2.1 proposing a fixed rear mechanism there is no need for the external back mechanism on the Ei-Foil. Hence, the foil can sit underneath the hull keeping in mind the need for wiring for motors and watertight design. Foils can be mounted from the back seen in Figure 18 where the foils mount onto struts [46] or mount from the side where the foil fully folds up in Figure 19 [47]. One of the concepts for the design of the rear mechanism will propose a similar idea of having the rear foil fold upwards on the Ei-Foil, keeping in mind the Ei-Foil only has one foil attached from the middle. This concept will incorporate the idea of a 180 degree scissor mechanism [48] shown in Figure 20 and Figure 21, allowing the foil to fully fold out the water.

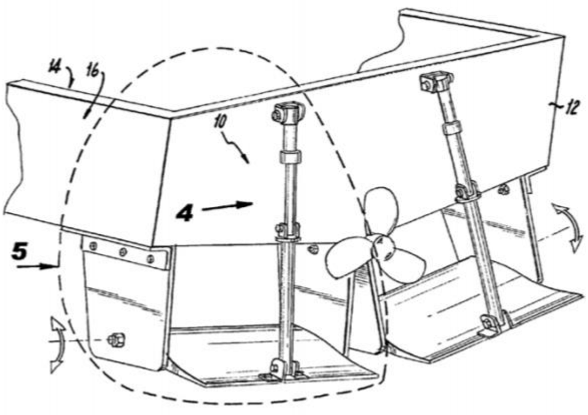


Figure 18: Hydrofoil attachment from behind [46]

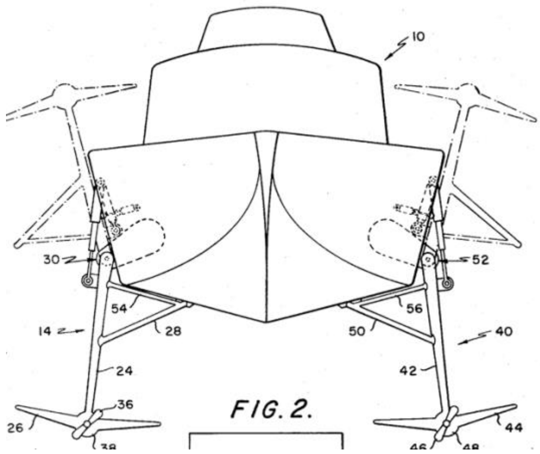


Figure 19: Folding mechanism hydrofoil retraction [47]

Figure 20: 180 degree scissor mechanism folded [48]

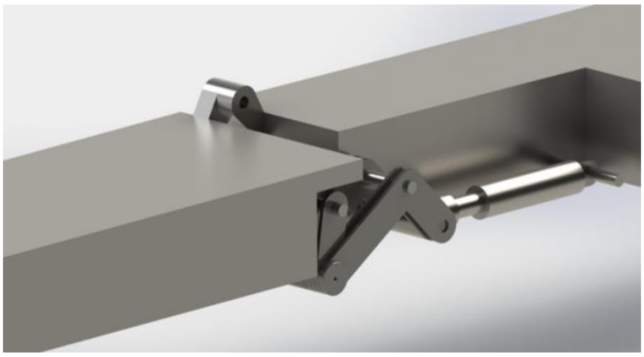


Figure 21: 180 degree scissor mechanism extended half view [48]

Another system used for hydrofoils is the retraction into the hull. Foils can be retracted by either using a rack and pinion mechanism [49] shown in Figure 22 or a pulley mechanism [50] shown in Figure 23. These retraction systems use simple designs to allow the foil to move in a vertical direction within the hull. The other concept design for the rear mechanism will incorporate the idea of using a retraction system as shown below. Both solutions will be fully analysed for the second part of this thesis.

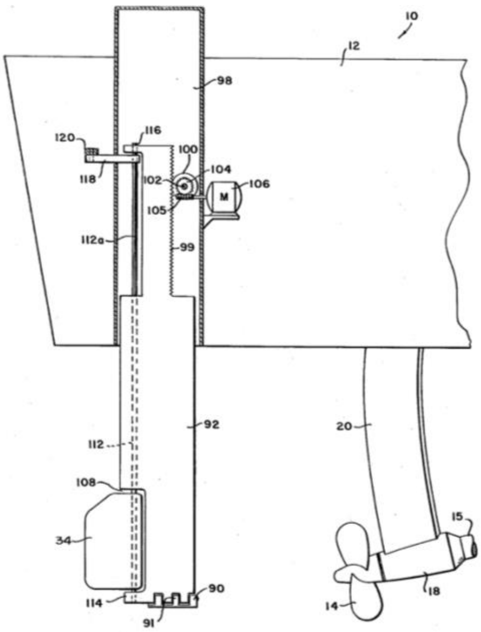


Figure 22: Rack and pinion mechanism retracted hydrofoil system [49]

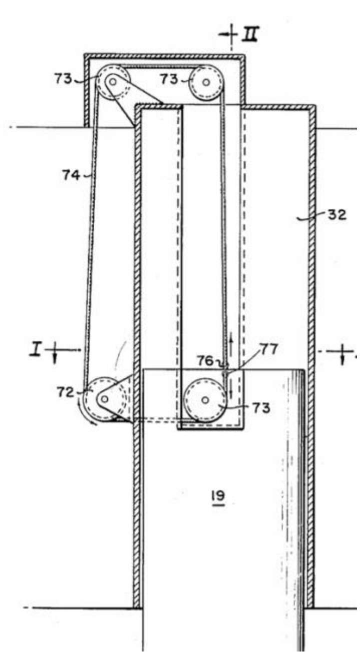


Figure 23: Pulley mechanism hydrofoil retraction system [50]

5 Analysis and Design Process

The following section describes the processes of hydrofoil stability analysis and the rear mechanism concept design. The requirements, constraints, tools used, framework to assess the analysis and design and the methodology will be described.

5.1 Hydrofoil Stability Analysis Process

The first part of this thesis is to conduct a stability analysis on the Ei-Foil hydrofoils. Due to unforeseen circumstances of COVID-19, time constraints proved difficult in which the proposed further analysis using a fluid dynamic software of ANSYS was unable to be utilised. Consequently, stability analysis was only conducted using XFLR5. XFLR5 is designed for aeroplanes thus hydrofoil analysis was limited. We were unable to model two foil masts therefore the masts were combined into one and doubled to account for the difference. Due to being unable to obtain a scale in time, the weight of the foils and hull and COG were approximated. It was assumed that for the base analysis, XFLR5 would be sufficient to produce results, and verified once trials are conducted. It was also discussed and accepted that based on results, a proper fluid dynamic software can be used in the future thesis to build on.

5.1.1 Analysis Requirements

The hydrofoil stability analysis analyses the hydrofoils to increase the stability of the Ei-Foil. Analysis is undertaken by varying different aspects of the foils to see how lift, drag and the overall stability is affected. The following aspects are required to be analysed allowing suggestions to increase stability:

- Foil configurations of Eppler, Aquila and Naca profiles
- Varying independent angles of attack on the front and back foils
- Adjusting chord and span dimensions of the foils
- Varying foils mast placements underneath the Ei-Foil

5.1.2 Analysis Constraints

There are several constraints outlined for the stability analysis. A major constraint is limited physical testing on the Ei-Foil has been conducted. Meaning the accuracy of the results can't be verified until further testing is complete. This adds uncertainty to the results as extra drag can't be accounted for. The verification of the results is only based on research and previous rider experience. This constraint ties in with time spent on fixing the craft to get it in working condition for testing. Another constraint is the assumption of the Ei-Foil weight and COG. These greatly affect the analysis of the craft as the COG plays a major role in determining stability and the effects of the hydrofoil placements. A further constraint, XFLR5 is a plane airfoil software tool, however, we are using it to model hydrofoils. Hence, from the analysis we are unable to determine the full fluid dynamic effects from the water on the hydrofoils. XFLR5 is also not a popular software tool, consequently there are not as many user guides or discussion forums, especially for hydrofoils.

5.1.3 Analysis Design Tools and Set Up

XFLR5 is the main tool used for the stability analysis which is a software tool to analyse airfoils, wings and planes operating at low Reynolds numbers [51]. Airfoil tools were used to extract the data points of the three foil profiles. These data points are entered into XFLR5 direct foil design to produce the profiles as shown in Figure 24.

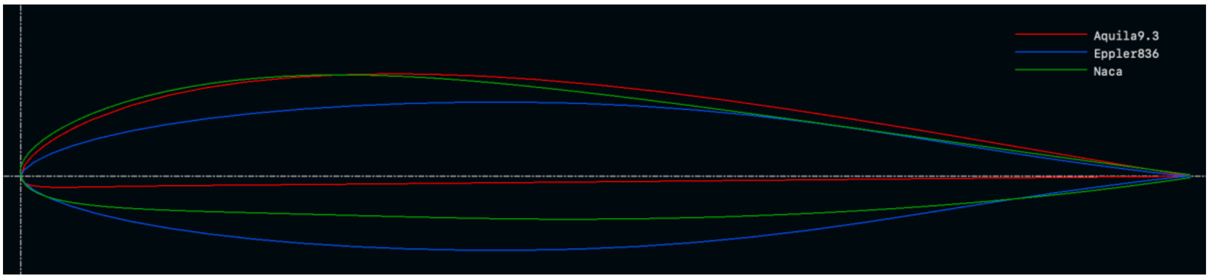


Figure 24: Foil profiles in XFLR5

From the airfoil profiles, a batch analysis is undertaken first on Xfoil direct analysis, to analyse the foil profiles, i.e. the shape of the foils. The calculated Reynolds number is used with a minimum of 1,500,000 and maximum of 2,500,000 with increments of 500,000 while using a -10 to 10-degree angle of attack range. However, for this particular analysis we have to consider that these profiles are based on analysis in air and not seawater. Next, using XFLR5's wing and plane design can model the front and back hydrofoils as a craft shown in Figure 25.

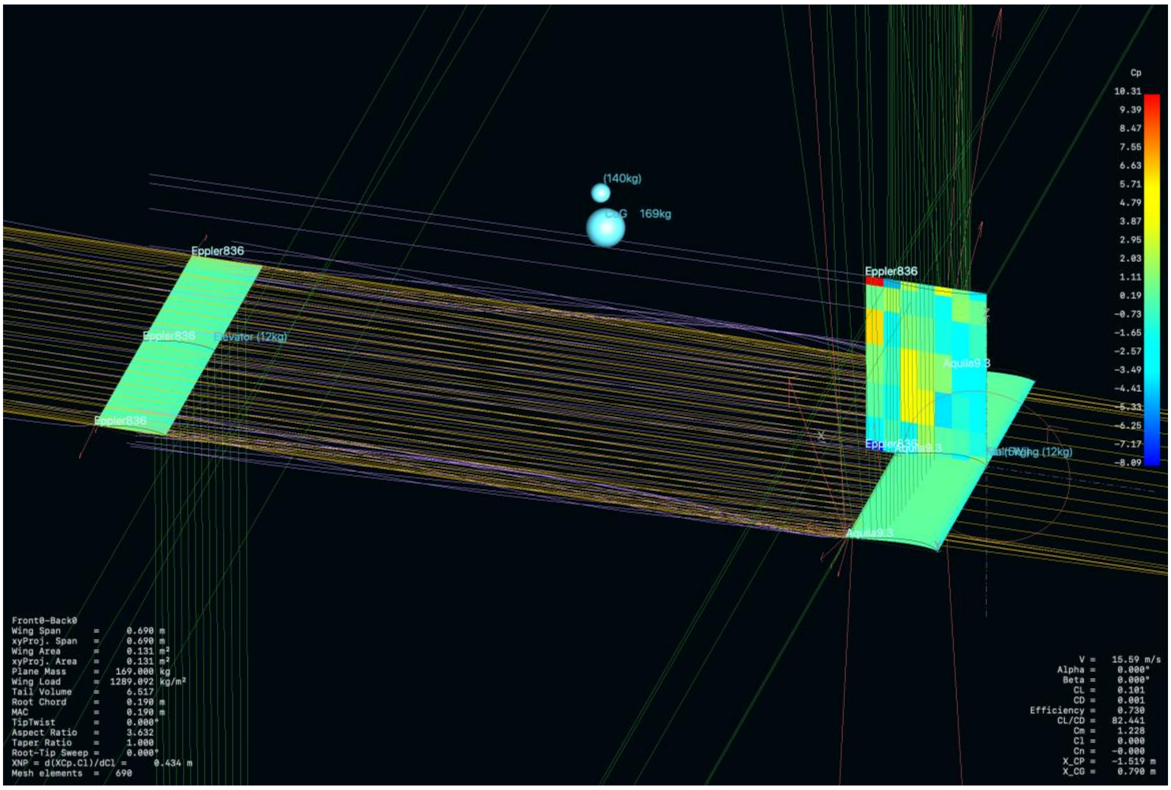


Figure 25: XFLR5 hydrofoil plane layout

The two masts were combined into one and doubled in length to account for the difference. The mast was placed on the front foil for analysis to account for the water effects hitting first. The front and back wings are modelled off the current design dimensions and placements.

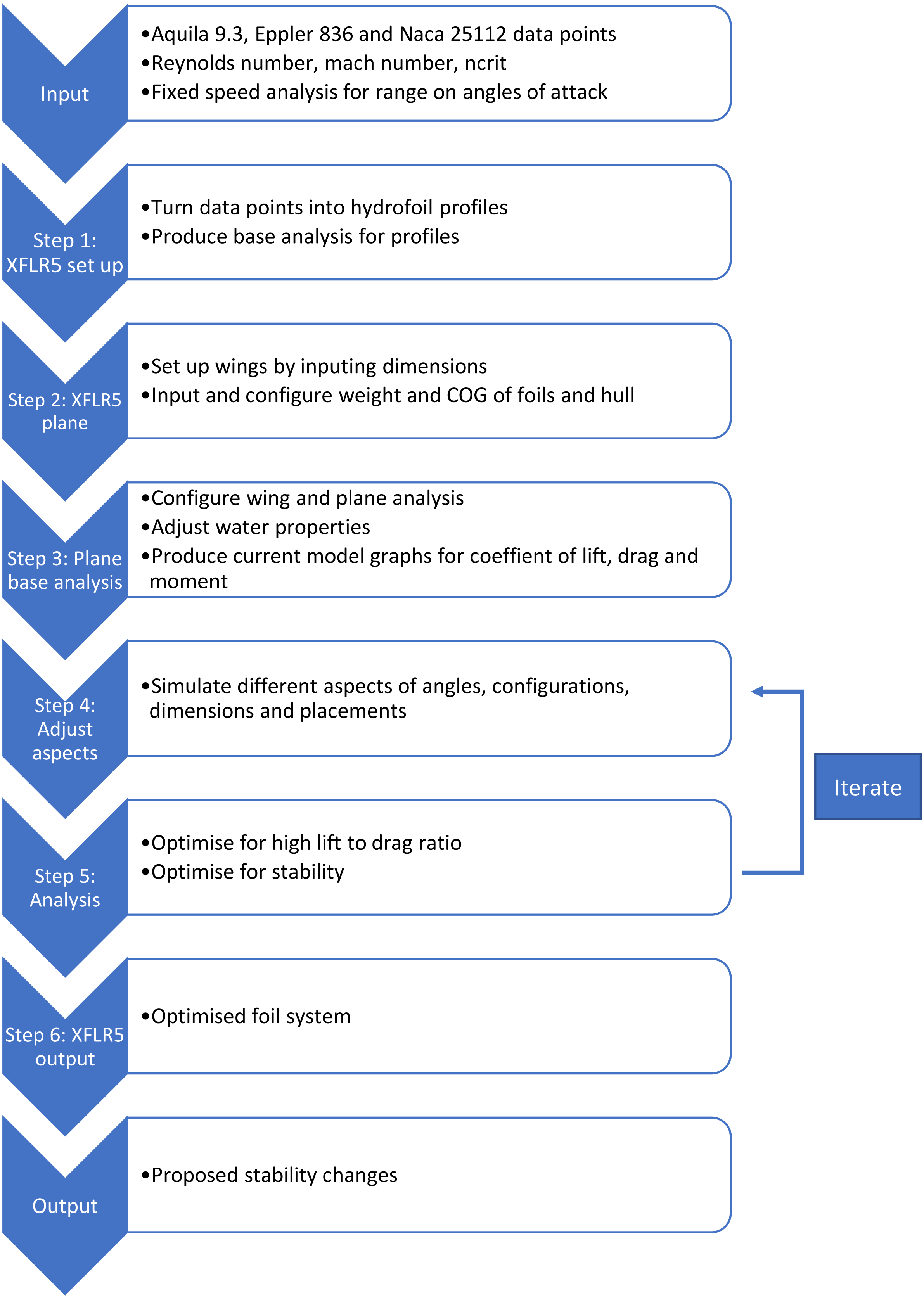
Here the assumptions of weights of the foils and hull are used as well as the COG of the Ei-Foil. After the plane of the foil is set up, the analysis of the plane can be defined. For stability, a fixed lift analysis type was used with a horseshoe vortex accounting for no sideslip. The Air data was changed to reflect water properties of speed and viscosity in 25degrees. These parameters would be used for all further analysis changing the different aspects of the Ei-Foil.

5.1.4 Analysis Framework

XFLR5 includes a variety of variables that can be measured against each other. It allows for analysis graphs to be completely modified based on what is desired. For the purpose of this thesis three main graphs were analysed against the angle of attack; coefficient of moment, coefficient of lift and coefficient of lift to drag. The Cm graph determines the overall stability of the craft. For a stable craft, the Cm curve needs to have a negative slope, with a steeper slope indicating increased stability. The Cl graph curves should be greater than zero. This indicates that the wing design allows the craft to lift up on the foils. The Cl/Cd ratio needs to be optimised. Ideally, we want a high lift with low drag, meaning at the desired angles we want to be as close to the maximum/peak of the curve as possible. However, we don't want to be at maximum as this is when stall sets in and creates nosedive of the craft or cause cavitation. The framework is accordingly summarised for the analysis of the stability of the Ei-Foils hydrofoils:

- Negative steep slope Cm
- Cl > 0
- Cl/Cd ratio near maximum

5.1.5 Hydrofoil Analysis Methodology



5.2 Rear Mechanism Design Process

The second half of this thesis is the redesign of the rear mechanism of the Ei-Foil. Using CAD, concept designs are produced to improve the rear foil attachment. Overall the design should consider a simple mechanical solution for foil retraction as well as adding value to aesthetics of the craft and rider convenience.

5.2.1 Design Requirements

The requirements for the second half of this thesis is to produce concept designs for the redesign of the rear external mechanism on the Ei-Foil. Requiring relocating the control box from outside the hull to inside. There is also the desired requirement of fixing the rear assembly to allow no movement of the back foil. Fixation of the rear assembly will be a short-term fix for testing and trial runs, however, the concept designs will incorporate the fixation of the rear. The produced concept design is required to:

- Limit the additional length from behind the hull
- Have the rear foil sit underneath the hull
- Allow convenient foil retraction

With these requirements in mind, two concept ideas will be proposed with the first having a retraction system into the hull and the second using a folding mechanism.

5.2.2 Design Constraints

There are a few constraints that the design faces. Firstly, the relocation of the control box. The control box currently sits outside the hull, taking up unwanted space and forces the rear foil to extend the length of the hull. The control box needs to be relocated to allow the rear foil to sit underneath the hull. The second is the trailer. With retraction desired and for the rear foil to sit underneath the hull, if the foil were to be moved now, it would not clear the trailer bungs. Therefore, the trailer poses a constraint on the way the concepts are designed. Another constraint is the motor wiring. The motor cables and sensor wiring currently run through the rear foil mast, therefore the retraction systems have to incorporate having wires through the mast. An unforeseen circumstance of COVID-19 as mentioned above challenged time constraints, with limitations on physically working on the ski. Adding to the time constraints the Ei-Foil itself not in working condition meant a lot of time is utilised trying to get the craft in working condition so the designs are closer to being implemented. Another design constraint is inexperience with CAD, hence time will be taken to learn how to use CAD software before producing concepts. Additionally, there is a financial constraint on the Ei-Foil. Although these designs will be concepts, consideration into the costs for fabrication, rearrangement and installation need to be considered. Ideally, fabrication should be constrained to the in-house workshop, and installation is constrained to the project team with help from the mechanical workshop. The above constraints will be taken into consideration when producing the concepts for the Ei-Foil rear mechanism.

5.2.3 Design Tools

CAD was used to produce concept designs for the rear mechanism of the Ei-Foil. It was assumed that Solidworks would be used which is a highly popular 3D CAD design software readily available on windows computers within the university. However, due to COVID-19 access to the university was restricted. Additionally, Solidworks was unable to be downloaded on a MAC laptop computer. Alternatively, Freecad was used to produce the CAD drawings. Freecad is an opensource 3D CAD modeler [52]. Although not used in industry, Freecad is widely used personally and correspondingly there are tutorials and help forums online for a beginner. There were some limitations of the software especially being a beginner of CAD, and for this reason, parts were slightly simplified for the CAD concept drawings.

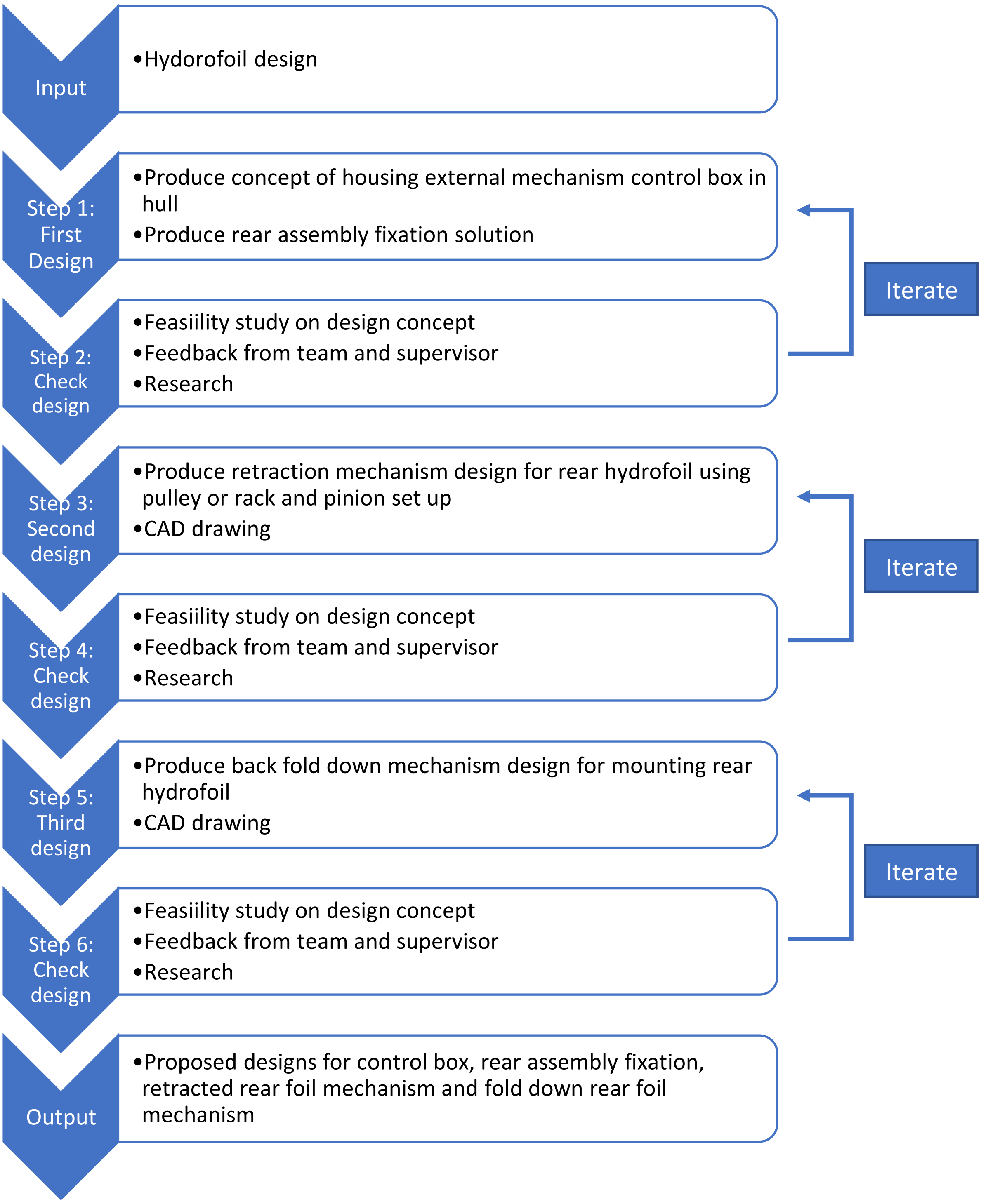
5.2.4 Design Framework

The framework is kept to the simplicity of the design. The design should add value to the Ei-Foil by overall:

- Having low-cost fabrication and implementation
- Providing convenience to the rider
- Acquire minimal space on the craft
- Eliminate the extra length behind the hull
- Use simple proven mechanical designs
- Add aesthetics to the craft
- Require minimum maintenance
- Allow for minimal trailer modifications

The above framework will allow evaluation of the proposed design concepts to contrast.

5.2.5 Rear Mechanism Concept Design Methodology



6 Hydrofoil Analysis Results and Discussion

6.1 Three Hydrofoil Profiles

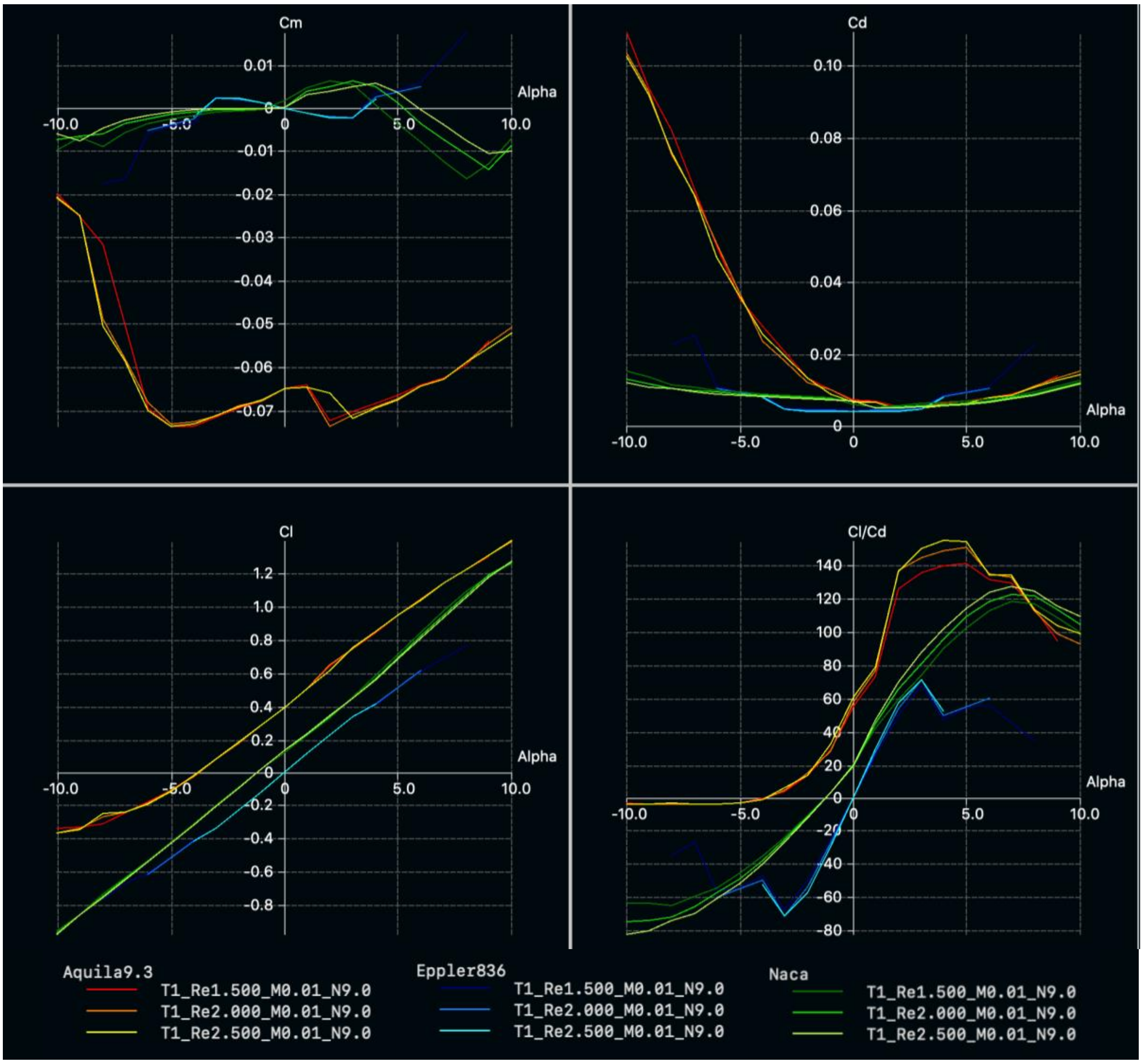


Figure 26: Foil Profile Results

The first hydrofoil analysis was conducted on three foil profiles; Aquila, Eppler and Naca, with the results produced in Figure 26. The Naca profile was used for comparison as it is the most self-stabilising foil due to reducing nose-down pitching moments. Proven in the Cm graph in the top left as there is a wider range of α where the slope is negative starting around 3 degrees. The Naca also has a more stable Cd at all angles. The Cl/Cd ratio graphs show the Naca reducing nose-down pitching moments as the maximum of the curve is smooth whereas the Eppler and Aquila all have sharp points where the Cl/Cd drops significantly. The Cm graph shows that both the Naca and Eppler have an operating point (balancing angle) at 0 degrees where Cm is 0. However, the Eppler show stability at low $\alpha's$ from 0 to 3 degrees while the Aquila shows stability at a narrow range of 1-2 degrees. The Aquila is the most efficient profile for producing lift explaining why this foil is chosen for the front foil, however, sacrifices stability. Nonetheless, all foil profiles show that they are capable of operating on the Ei-Foil.

6.2 Varying Foil Configurations

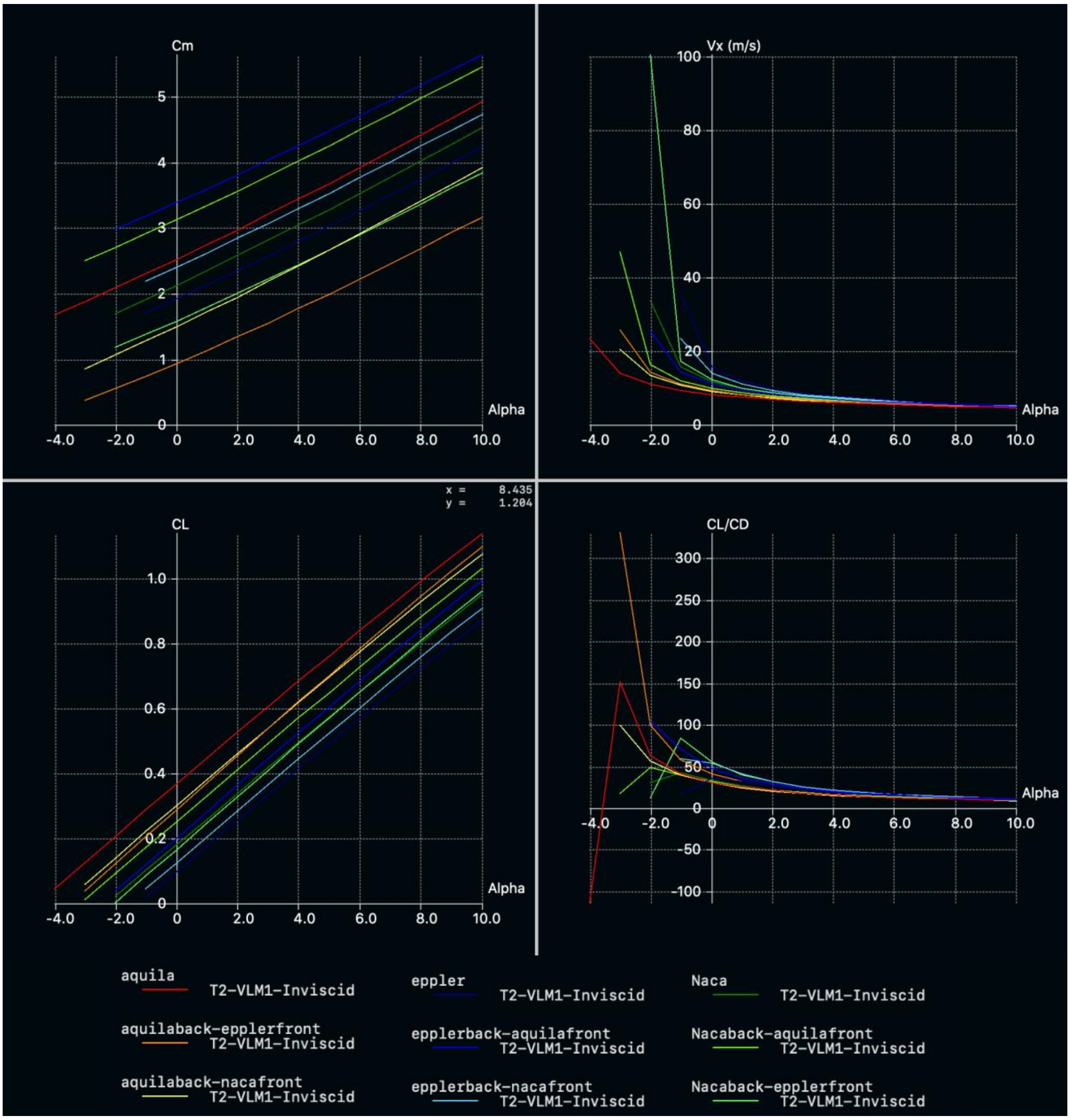


Figure 27: Foil Configuration Results

The second analysis is undertaken by converting the profiles into wings including masts to produce the hydrofoil craft as shown in Figure 25 in section 5.1.3. The layout and dimensions of the Ei-Foil was kept the same as current with only varying the profile pairs with results shown in Figure 27. Varying different foil configurations did not produce any promising results. The Cm graph indicates that no pair is sufficiently stable as all curves have a positive slope and are very similar. The Cm graph having positive slopes currently make sense as the Ei-Foil has the Eppler on the back and the Aquila on the front which is having stability issues. On the other hand, it is interesting to see that two Eppler foils together are more efficient than two Aquila foils while two Naca foils have the most efficient Cl/Cd ratio. Despite with profile analysis, the Aquila had the best Cl/Cd efficiency.

6.3 Varying Foil Angles

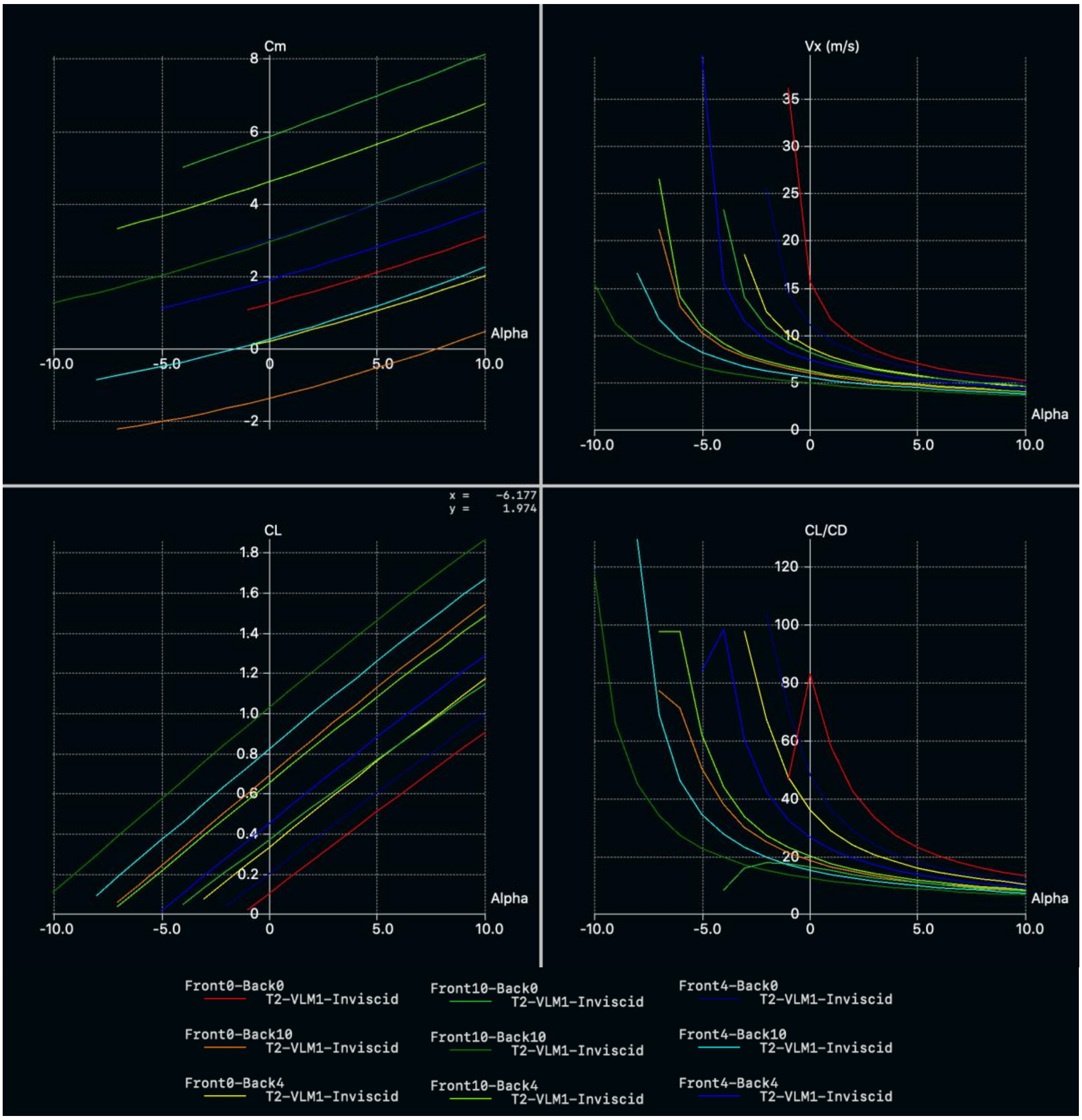


Figure 28: Foil Angle Results

The third analysis is conducted by changing the back and front foils α independently to each other. The original foil profiles of the Eppler on the back and the Aquila on the front was kept with the current dimensions. Again, from Figure 28 there are no convincing stability results from the variation of $\alpha's$ however, it is shown that the Cm curves vary greatly and have a wider range than changing foil configurations. It is shown that at higher angles of both wings, greater lift is generated however, from the Cl/Cd graph the efficiency is low meaning high angles also produce increased drag. Comparing these results to the current set up, there were trials done previously on the Ei-Foil to change the α of each foil independently, and the trials indicated similar results of no combination showing a distinct advantage as the joysticks were still heavily required to produce stability and allow the craft to stay on the foils.

6.4 Varying Chord and Span

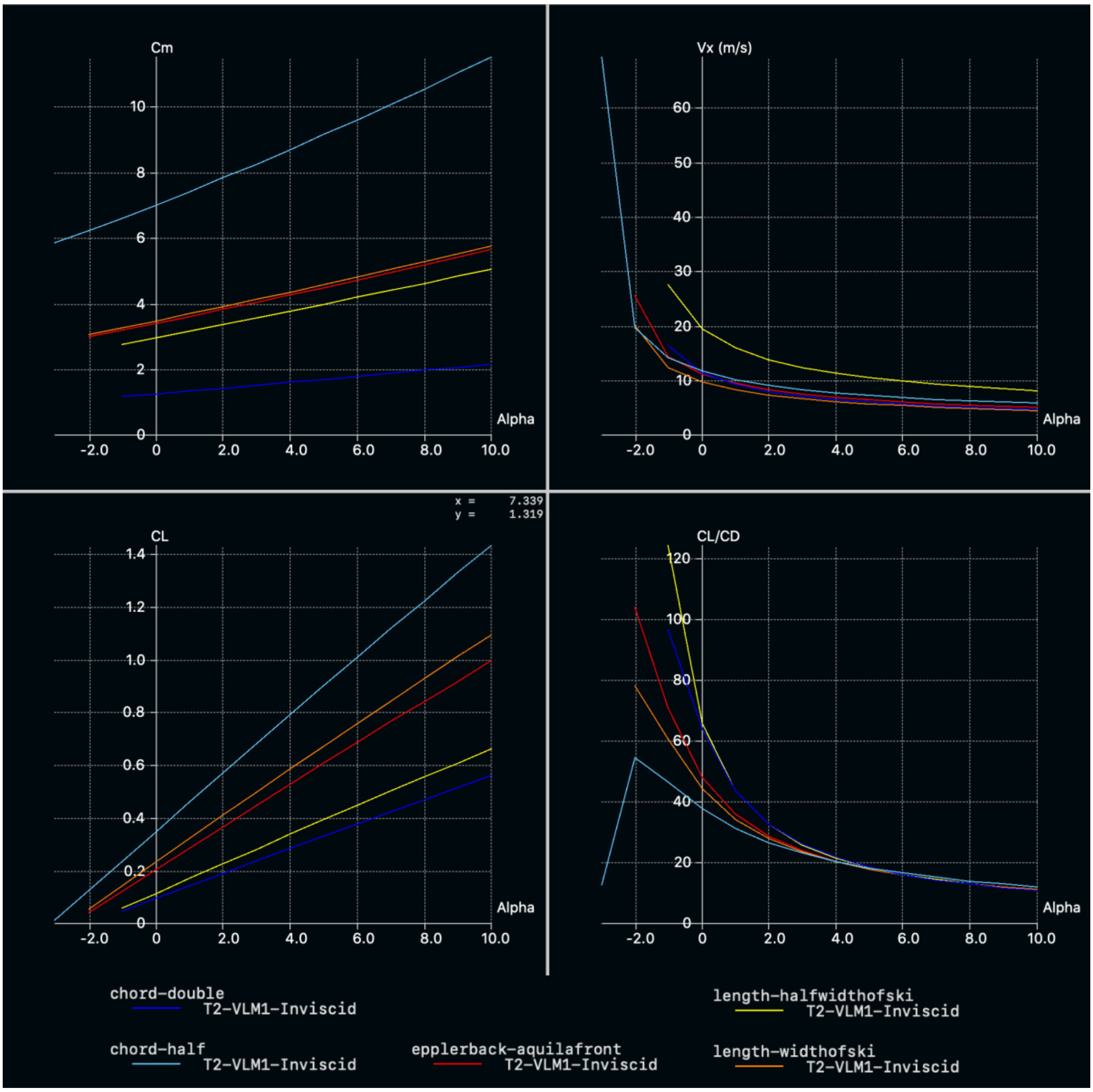


Figure 29: Chord and Span Results

The fourth analysis for the hydrofoil stability is varying the chord and span (width and length) of the wing profiles with the results shown in Figure 29. From the variations, the Cm graph has changed dramatically from previous analysis indicating the dimensional changes affect the stability of the graph. However, there is still no self-stability of the craft with no negative slopes. The Cl/Cd graph shows that there are no significant changes from the researched optimisable α around 3-4 degrees.

6.5 Varying Wing Placements

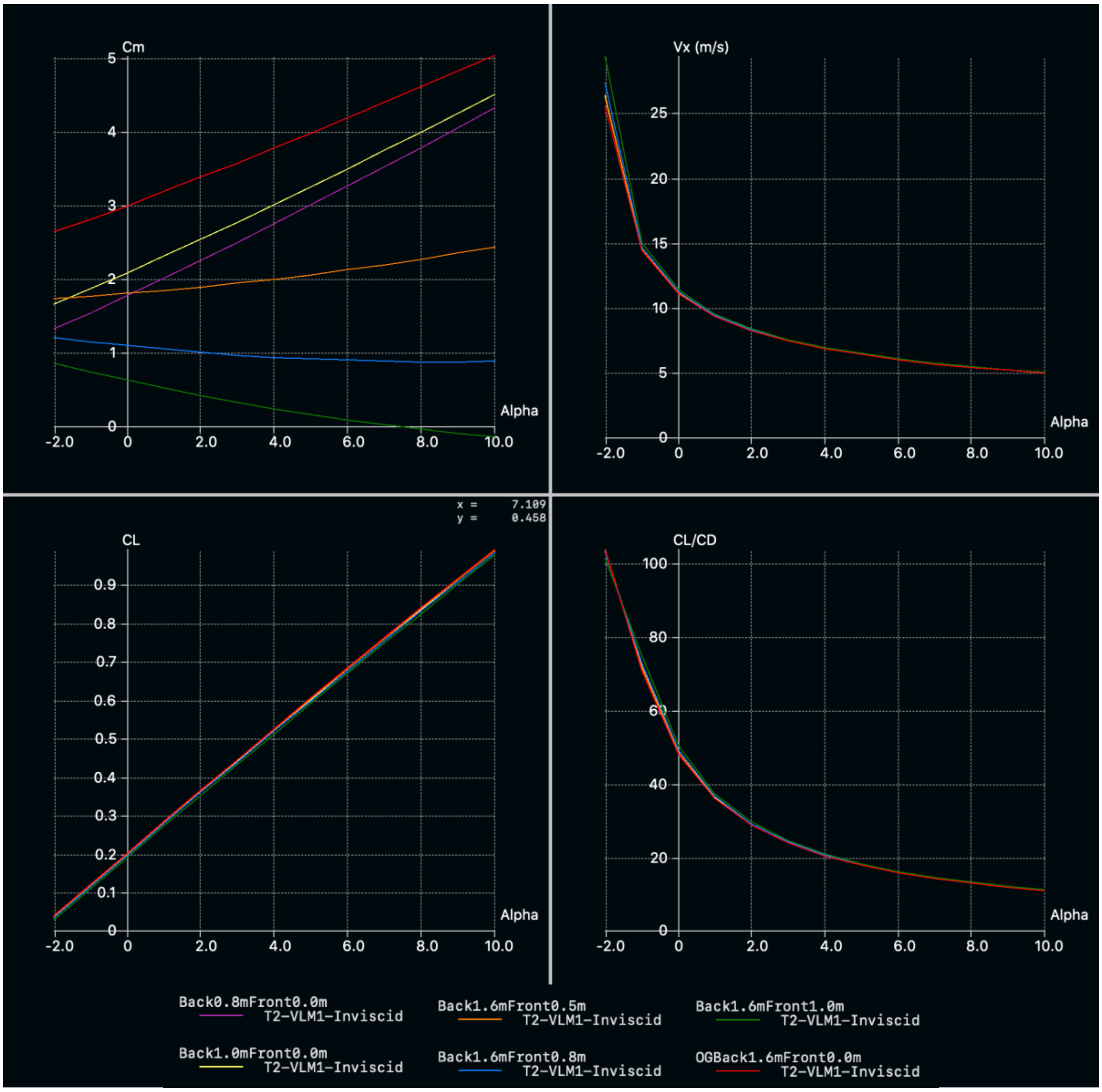


Figure 30: Wing Placement Results

The fifth and final analysis was conducted by varying the placements of the front and back wings represented in Figure 30. The red curve in the analysis represents the current set up. The placements of the mast have a very limited change in the lift and drag of the craft. In contrary mast placements have a big effect on Cm and hence the stability of the craft. Moving the front mast closer to the COG of the Ei-Foil shows an increase in stability with a negative slope. The front mast directly under the COG shows the most stable configuration with the steepest slope. Therefore, to increase the stability of the Ei-Foil the movements of the masts need to be taken into consideration. Although, currently the front mast retracts up into the hull and moving the front mast closer to the middle of the craft is difficult as retraction would be affected as the battery box currently sits in the middle and the height of the hull is minimal in that section of the Ei-Foil.

7 Rear Mechanism Design Concepts and Discussion

7.1 Control Box

Figure 5 in section 2 above showed the silver control box acquiring extra room at the back of the Ei-Foil. Due to underlying issues with motor controllers, waterproofing and noise, the control box has since been moved inside the hull which freed up extra space shown in Figure 31. The new control box designed sits on top of the battery box and is currently being rewired. This movement eliminates the need for many unwanted cables to run externally from the hull which created noise. The only cables coming out from the hull to the back-foil mast now include motor control, depth sensor and servo cables which all connect through an Amphenol waterproof connector. The new layout includes a closed-loop water cooling system for the motor controllers which runs of a small pump. The water containers sit below the two metal boxes to the right of Figure 32 to allow water circulation once the Ei-Foil is powered and runs for a minute after the craft is powered off. The freed space provides a major advantage, allowing the rear foil to be mounted within hull length. Thus, allowing for redesign of the rear mechanism discussed in further detail below.

Figure 31: Space after Removal of Box

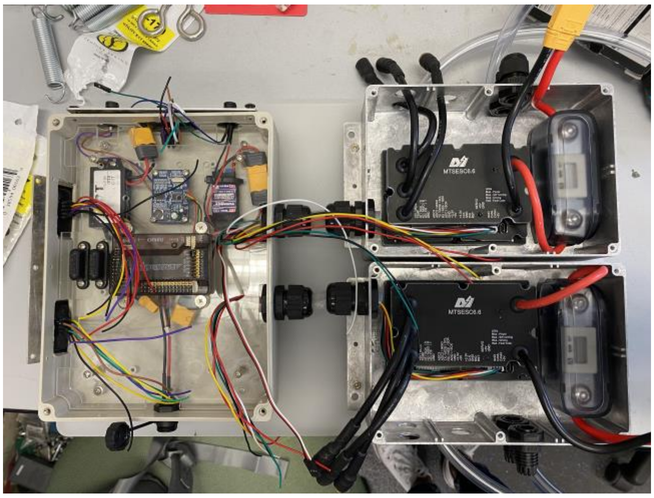


Figure 32: New Control box Layout

7.2 Rear Assembly Fixation

From the literature review in section 4.2.1 it is evident that the rear mechanism should be fixed and turning should be controlled by alternative control systems. The proposed solution to a short-term fixation for trialling uses a turnbuckle mechanism shown in Figure 33. The idea is to allow for the fixation interchangeable at this stage for the existing steering rod connection to the back of the foil as seen in Figure 31 (steel rod connected to bracket fixed to the hull). The new rod will be fixed in place with a new bracket attached to the rear of the hull to allow for both the steering rod and new rod attachment points. Allowing exact dimensions, so the rod has limited movement. Disconnecting the steering rod allows for free movement of the steering to control the aileron and motor variable speed. Coding is updated to account for the aileron to bank into turn but also counteract to ensure the Ei-Foil stays balanced and does not roll. The motors will also help for turning for example if turning left the right motor will have more speed than the left to allow the craft to turn. Testing is yet to be done on the foil due to difficulties with COVID-19 and other unforeseen problems occurring. Once testing is undertaken with the new fixation device, feedback can be given into whether this is a sufficient amount of turning. From the literature review, it is evident that rudders are better suited to help with turning. Therefore, it is proposed that a rudder be trialled later for steering. This would also produce sharper steering i.e. when coming into dock at a jetty or when needing to quickly avoid other vessels in the water. Due to time constraints, the design could not be implemented further as other areas were prioritised. The following concept designs for the rear mechanism take into consideration the fixation of the rear foil mast.

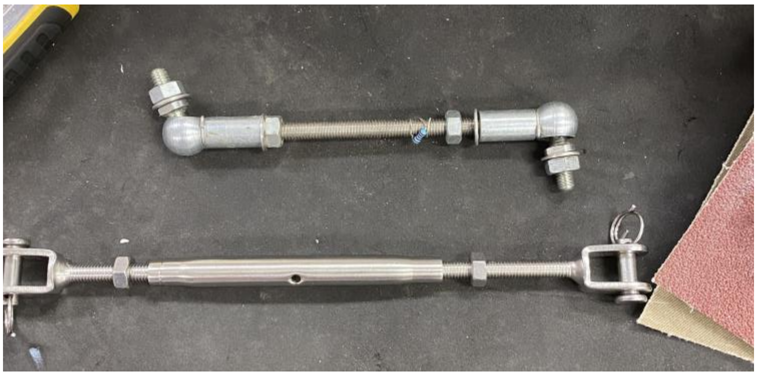


Figure 33: Turn Buckle Mechanisms

7.3 Concept 1

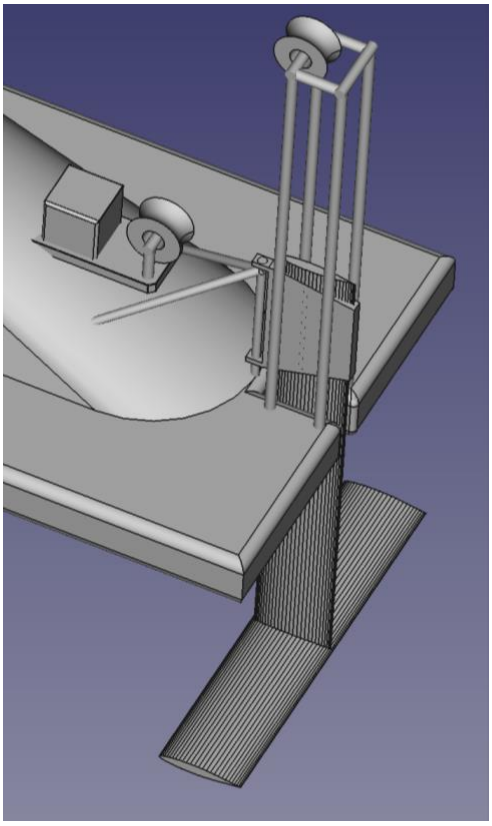


Figure 34: Concept 1 CAD Model Top View

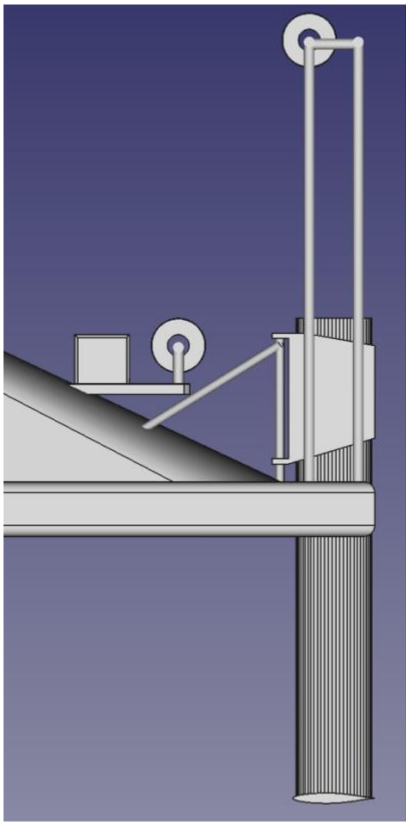


Figure 35: Concept 1 CAD Model Side View

During the first concept design phase, the rack and pinion mechanism retraction system was eliminated due to requiring more space within the mast to allow for gear teeth. This required modification to the foil mast and bracket which at this stage was undesirable. The pulley system idea was explored further with the first concept in Figure 34. A new mounting system for the foil bracket insured the foil sat underneath the hull, utilising space previously occupied by the control box where Figure 35 shows the mechanism does not exceed the hull length. The design uses the same foil bracket with new supporting poles. The support poles are angled through the hull to ensure forces are accounted for, with a single pole through the front of the bracket allowing fixation and no turning of the bracket. The cut out from the hull is minimal, however, if fixation of the steering isn't desirable, the cut out can be increased to allow the foil to turn, with steering rod and bracket added back. The retraction system includes a winch mounted to a supporting bracket at the back of the hull. The winch can be hand or electric with a simple button on the steering for ease of the rider. The winch works of a pulley system allowing the cable to run underneath the first pulley and around the top second pulley where it is attached to the inside of the foil mast. The idea of mounting the second pulley seemed somewhat tricky, as due to the way the foil is mounted on the bracket, the brace requires extra length to retract the whole foil upwards. An updated concept design in Figure 36 modified the angles of the brace improving the stability and sturdiness.

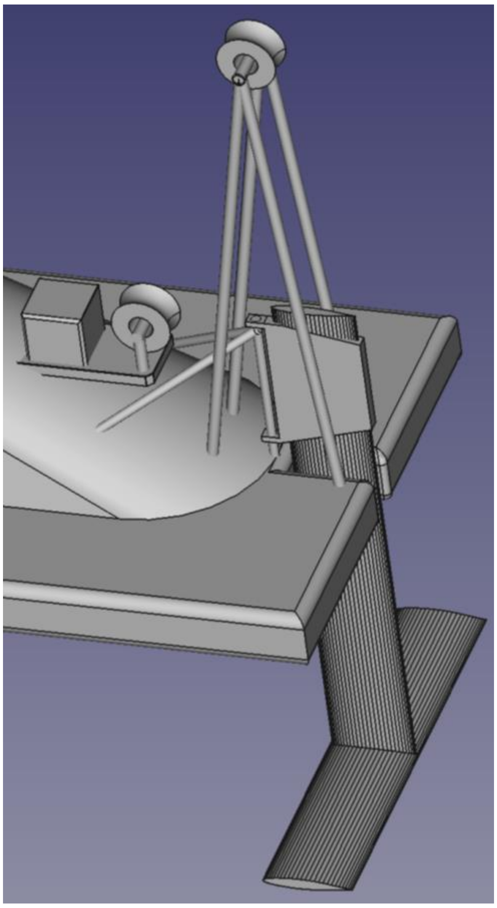


Figure 36: Concept 1.1 Angled Brace

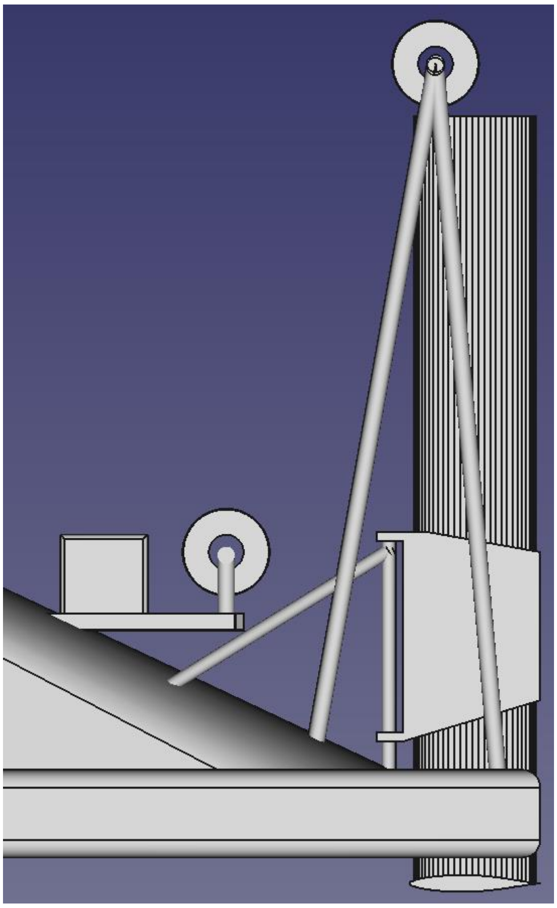


Figure 37: Concept 1.1 Retracted Foil

The concept ensures full retraction of the foil shown in Figure 37, enabling the clearance of the trailer or requiring minimal movement of the back last trailer bung. It allows for a simple mechanical solution such as winch pulley system which is easy to implement. The fabrication of supporting poles and brackets are able to be manufactured in-house at the workshop and installed by project team members. The motor cables will be required to run through a cable carrier allowing the full extended cable while riding and rolled up while retracted. Overall the design is easy to construct and implement. However, the back second pulley brace is undesirable taking extra space due to the height needed for retraction. It also poses a safety concern due to winch cable exposed and extra cable length required for retraction. This can all be hidden under a cover but again will require extra space and overall will not add to the aesthetics of the Ei-Foil. Although the design isn't desirable on the rear foil, the retraction system can be manipulated and used on the front foil. The front foil currently retracts into the hull manually. The winch pulley system can be manipulated for inside the hull and can allow easy retraction for the front foil.

7.4 Concept 2

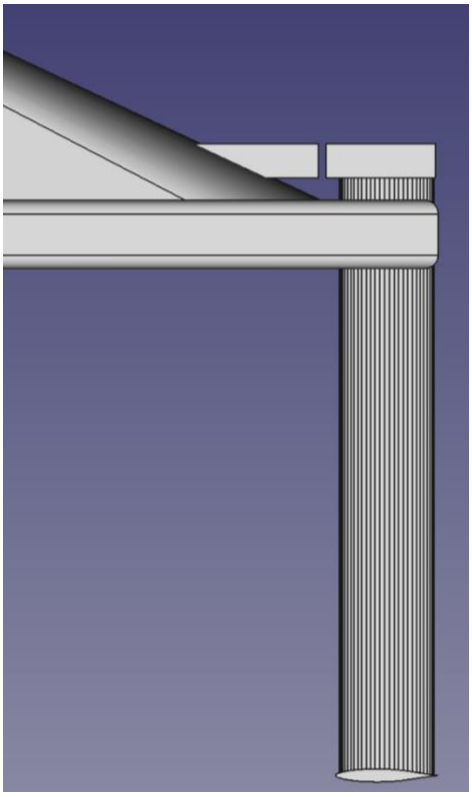


Figure 38: Concept 2 CAD Model Side View

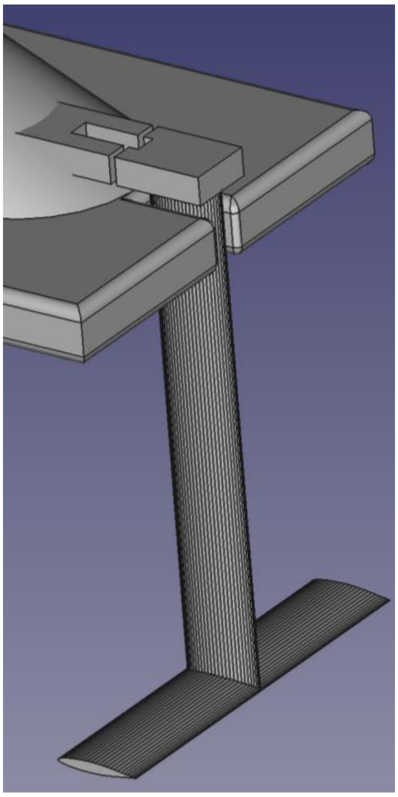


Figure 39: Concept 2 CAD Model Top View

Concept design 2 of the rear mechanism incorporates a 180-degree folding mechanism idea described in section 4.2.2 from Lampropoulos [48]. This allows for a complete remodel of how the foil attaches to the hull seen in Figure 38 and Figure 39. To secure the assembly a mounting plate attaches to the back of the hull, housing the bracket and hydraulic arm within. The foil mast is required to be mounted from the top which proves difficulty for wiring. The wiring can either be through the mounting plate on either side of the hydraulic arm, through the foil bracket and into the foil internally. Alternatively, the wiring can run underneath the mounting plate and into the side of the foil. Both require extra length and cable flexibility for the foil to be fully retracted. The attachment from the top of the mast allows the foil to be mounted closer down the hull, hence allowing the total length of the mast to be reduced with minimal foil length required for mounting and foil length in the water. This concept design however does not allow the rear mechanism to rotate, the steering has to be fixed. The retraction system of concept 2 is shown in Figure 40 and Figure 41.

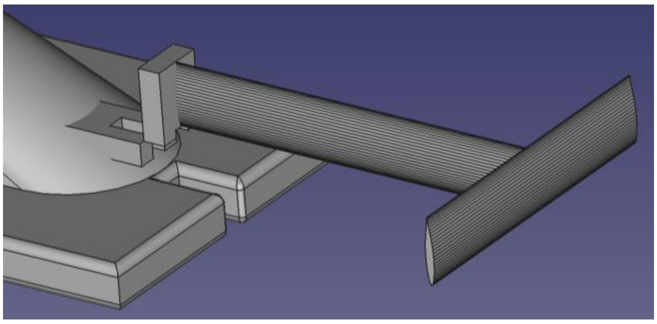


Figure 40: Concept 2 Mid Retraction

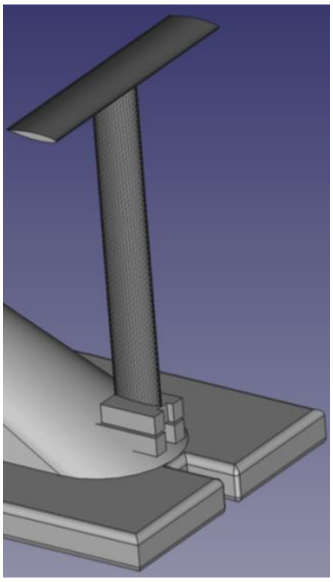


Figure 41: Concept 2 Fully Retracted

Similar to the Boeing retraction the scissor mechanism allows for full retraction of the foil and instead of sitting underneath the hull, the foil is completely out the water. Bringing added benefit of docking on shore, currently not possible due to the ground scraping the foils. The hydraulic arm will be wired electrically allowing a retraction button on the steering convenient to the rider. Additionally, allowing the arm locked into place when retracted and when riding. The back hull allows enough room for the retracted foil to not interfere with having a second rider. The bracket can be fabricated in house and only the hydraulic arm system will need to be purchased. Overall the design uses a hydraulic arm mechanical mechanism for simplicity. It allows for minimal utilised space, full retraction of the foil and adds to the aesthetics of the Ei-Foil.

8 Conclusion

8.1 Hydrofoil Stability Analysis Conclusion

Overall the XFLR5 data provides a base of the hydrofoil stability analysis. Varying foil configurations, foil angles and chord and span lengths display no promising results in improving the stability of the Ei-Foil. However, these variables can affect the coefficient of lift to drag which is desired to be optimised. Varying placements of foil masts show a direct relation to the stability of the craft and is evident, to increase the stability of the Ei-Foil, moving the masts need to be considered. The results, however, require some improvements as the weight and COG of the Ei-Foil were assumed. In future, these need to be obtained and inputted correctly into the analysis to produce accurate results. Upon newly produced results, future extensive trials need to be conducted on the Ei-Foil to verify the accuracy and range of results. Trials will also confirm the extra drag from the motors and hull which can be inputted into XFLR5, improving the accuracy. Once verifying the results, desired changes can be analysed in XFLR5 before physically adapting to the Ei-Foil. Moving the masts however will prove difficult for retraction and greater research for a way around the battery box is required. It is also desirable for future work on the hydrofoil stability analysis to model the Ei-Foil in a proper fluid dynamic software, which would help with the accuracy of the results and allow simulations without physically testing on the Ei-Foil.

8.2 Rear Mechanism Design Conclusion

Although undesired on the rear mechanism concept design one still adds value to the project as it can be manipulated and used on the front foil retraction system. Concept design two is a simple and neat design for the rear foil mechanism. It meets the design requirements of removing the extra length added to the hull, allows the foil to sit underneath the hull and allows easy retraction of the foil by the rider. It adheres to the framework of low-cost fabrication of the bracket done in the workshop, adds convenience to the rider with retraction and allowing onshore docking, requires minimal space, uses a simple mechanical design, adds aesthetics to the craft and limits trailer modification. Improvements of the design section can be made to the CAD drawings as they were simplified due to only beginning to use CAD. This will ensure the drawings can display further detail and allow for more complex parts like the winch system, cables, hydraulic arm and bracket shapes. Future work is required for the concept design to move forward. Once test trials on the Ei-Foil are undertaken, forces on the foil can be confirmed. This ensures that the proper rated hydraulic arm can be ordered for the weight and forces when the foil is in the water and the arm is locked. This will also confirm the size of the bracket requiring fabrication to hold the foil, and if any other supporting frame is required underneath the bracket within the hull. It will also be more evident if the cables can run through the bracket or should run underneath. The design can move out of concept stage and through the design phases ready for fabrication and implementation. The design, however, is a big change to the Ei-Foil so consultation with further engineers is recommended before the rear end of the Ei-Foil is changed. Overall, the project team are happy with the concept design and will be progressing further beyond this thesis to ensure the design is acceptable.

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