UNIVERSIDAD EUROPEA DE MADRID

ESCUELA DE ARQUITECTURA, INGENIERÍA Y DISEÑO

DEGREE IN AEROSPACE ENGINEERING

FINAL PROJECT REPORT

DESIGN OF AN AC75 HIGH-PERFORMANCE SAILING YACHT

JUAN GUERRERO SANCHO

09/06/2023

TITLE: DESIGN OF AN AC75 HIGH-PERFORMANCE SAILING YACHT

AUTHOR: JUAN GUERRERO SANCHO

SUPERVISOR: RAÚL CARLOS LLAMAS SANDÍN

DEGREE OR COURSE: AEROSPACE ENGINEERING

DATE: 09/06/2023

ACKNOWLEDGEMENTS

Raúl Carlos Llamas Sandín

Nicolas Bailey

Víctor Guerrero Ferrer

Gema Sancho Zamora

Jimena Cueto-Felgueroso Álvarez

Manuel Guerrero Sancho

Víctor Guerrero Sancho

INDEX

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

CFD	Computational fluid dynamics
NYYC	New York Yacht Club
FRP	Fibre reinforced polymer
LCG	Longitudinal centres of gravity
MWP	Measurement waterline plane
TRP	Transom reference plane
LCP	Longitudinal centre plane
FCS	Foil cant system
WSP	Wing symmetry plane
$\mathbf{G_F}$	Foot girth
$\mathbf{G_{25}}$	25% girth
$\mathbf{G_{50}}$	50% girth
$\mathbf{G_{75}}$	75% girth
$\mathbf{G_H}$	Head girth
ETNZ	Emirates Team New Zealand
LRPP	Luna Rossa Prada Pirelli
AM	American Magic
IB	Ineos Britannia
$\mathbf{C_L}$	Lift coefficient
$\mathbf{C_D}$	Drag coefficient
$\mathbf{C_m}$	Moment coefficient
ϱ_{water}	Water's density
$\mathbf{A_{wing}}$	Wing's area
$\mathbf{V_{wind}}$	Wind's velocity
L	Lift force
D	Drag force
E	Effort force

ABSTRACT

The objective of this project is the study and design of the four main elements of an AC75 yacht: the hull, the foils, the rudder and the mainsail. To accomplish this objective, an understanding of the historical and theoretical background of the America's Cup is required, which is followed by the study and analysis of both the AC75 Class Rule and competitors of the 36th America's Cup. A preliminary design is devised for each of the elements, describing their design intent, and is then analysed in order to model a final design of each component and of the final product. Throughout the project, a better understanding of how the yacht works is gained and consequently the design focus evolves past the perspective of aerospace engineering. One of the elements of the mainsail design improves its aerodynamic efficiency by more than 5% by taking advantage of possible Class Rule interpretations and innovative design inspired by the aerospace sector.

RESUMEN

El objetivo de este proyecto es el estudio y diseño de los cuatro principales elementos de un velero AC75: el casco, los foils, el timón y la vela mayor. Para cumplir este objetivo, se requiere un entendimiento del contexto histórico y teórico de la Copa América, seguido por un estudio y análisis de tanto la Norma del AC75 como los competidores de la 36ª Copa América. Se ha ideado un diseño preliminar para cada uno de los elementos, describiendo la intención de diseño, que es luego analizado para así modelar un diseño final de cada componente y del producto final. A lo largo del proyecto, se adquiere un mejor entendimiento de cómo funciona el velero y en consecuencia el enfoque de diseño evoluciona más allá de la perspectiva de la ingeniería aeroespacial. Uno de los elementos del diseño de la vela mayor mejora la eficiencia aerodinámica en más de un 5% aprovechando posibles interpretaciones de la Norma e innovando en diseños inspirados por el sector aeroespacial.

CHAPTER 1. INTRODUCTION

1. 1. PROBLEM APPROACH

The America's Cup is the highest-level sailing competition in the world. It has been at the forefront of sailing innovation for many years, to the point of being used as a testing ground for aircraft technologies by companies such as Airbus. In fact, the similarities between aircraft and the latest AC75 sailing yacht are plenty, and currently 5 teams from around the globe are working tirelessly to design the best AC75 to win the 2024 America's Cup (37th America's Cup) in Barcelona. The AC75 is a monohull that features hydrofoils, which similarly to wings in aircraft, lift the yacht out of the water, highly reducing drag and reaching record-breaking speeds.

Figure 1: Photograph of two AC75s [W. Ricketson]

The design of an AC75 requires knowledge in Aerodynamics, Hydrodynamics, Materials, Structures, Stability and many more areas which will be explored in this report. The design of the AC75 is bound to certain rules covered in the AC75 Class Rule, but despite this, the four boats featured in the 2021 America's Cup (36th America's Cup) were extremely different to each other, and much information can be extracted from the engineers' takes on the boat design when contrasted against their performance during testing and in the competition.

The main objective of this project is to design an AC75 high-performance sailing yacht that is capable of winning the America's Cup. To accomplish this task, a very methodical approach must be taken. Firstly, it's important to understand the AC75 Class Rule, with which the yacht must comply, while at the same time looking for possible ways to interpret said rule in order to obtain an advantage. Additionally, other sources will be investigated for a better understanding of the competition and the approaches of each team. Due to the secrecy of the teams, it will be important to consult investigative journals and analyse photographs of the yachts.

Secondly, the practical and creative part of the project will involve thinking of numerous designs through drawings and models of the different parts which form the yacht, being the hull, mainsail, foils and rudder the most important of these parts. The models will be analysed using computational fluid dynamics (CFD) and they will enter a design loop in which different parameters will be altered to come up with the best possible solution within the Class Rule. Finally, an assembly model with all the parts will be created as the final product.

1.2. PROJECT OBJECTIVES

As previously mentioned, the main objective of the project will be to **design an AC75 high-performance yacht capable of winning the America's Cup**. The secondary objectives which will lead to the accomplishment of this main objective will be the following:

- To study and understand the AC75 Class Rule and look for possible interpretations that may offer an advantage.
- To study, understand and find the advantages and disadvantages of the previous designs from all the teams during the 36th America's Cup.
- To design and analyse an efficient hull which takes into account the aerodynamic, hydrodynamic and hydrostatic aspects to achieve low drag, fast take-off from the water's surface and stability.
- To design and analyse low drag foil wings capable of lifting the yacht with the necessary control surfaces.
- To design and analyse a low drag rudder that will allow the crew to control the yacht efficiently.
- To design and analyse an efficient mainsail which provides the yacht's thrust with the necessary structural elements that allow for variable camber.

CHAPTER 2. BACKGROUND AND THEORY

2.1. HISTORICAL BACKGROUND

The America's Cup is the oldest international sporting competition. The first race dates back to 1851. Until that time, The Royal Yacht Squadron's members were the only ones who participated in British sailing races. In 1844, the New York Yacht Club was founded, and with it, a competitiveness between the clubs was born. William Brown, a boatbuilder of the United States' East Coast, offered one of the six founding members of the NYYC to build a sailing vessel faster than any other, which would later be baptised as the 'America'.

America crossed the Atlantic to attend a competition in the Isle of Wight against the best English yacht clubs. Their main advantage was that they could sail closer to the wind's direction than its competitors. America was competing against the most emblematic yacht clubs of England during that entire summer. In the most recognizable race, the Hundred Guinea Cup hosted by the Royal Yacht Squadron of Great Britain, America managed to win the cup which later became known as the America's Cup.

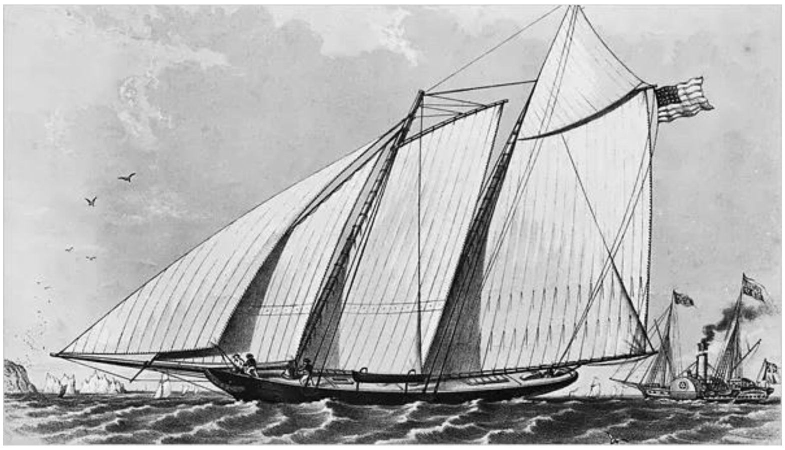


Figure 2: The America yacht

The cup was taken back to the NYYC, and from the 1920s until today, the America's Cup has had the same structure: one defending vessel and one challenging vessel. Whoever wins, gets to take the America's Cup back home. It has been a common aspect since the start of the America's Cup that its boats have the latest and most radical technology and designs found in the entire globe. In the beginning of the competition, the terms for the challenging yacht had huge disadvantages. Nowadays, the Challenger and the Defender work in unison to create the Class Rule that will define the vessel's design, and other challengers can join as well.

The 36th America's Cup was celebrated in 2021 off the coast of Auckland, New Zealand. It saw the challengers American Magic and Ineos Britannia battle against the Challenger of Record, Luna Rossa Prada Pirelli, and ended in the victory of the Defender Emirates Team New Zealand over Luna Rossa in the final Cup race. The sailing vessel of this edition, the AC75, is a monohull yacht that foils over the water's surface using two foil wings which are alternated depending on the ship's course. The differences between the four teams in terms of design were notable, and different interpretations of the Class Rule meant the difference between having an advantage or falling back. The next edition, the 37th America's Cup, will be celebrated in Barcelona and will introduce a fifth team, Alinghi Red Bull Racing. In this edition, Ineos Britannia will take the place of Challenger of Record and the AC75 will be maintained, with slight changes to the Class Rule.

2.2. THEORETICAL BACKGROUND

The rules that govern the forces and moments of a sailing boat are very similar to those of an aircraft. To explain how a conventional sailboat moves forward, two areas must be analysed separately: the forces in the sail and the forces on the keel.

On the sail, a certain wind velocity acts on the sail with a particular angle of attack. The sail's shape provides it with camber and, similarly to an aircraft's wing, produces a lift force perpendicular to the wind velocity, as well as a drag force in a parallel direction to the wind velocity. The sum of these forces creates an effort force, as seen in *Figure 3*.

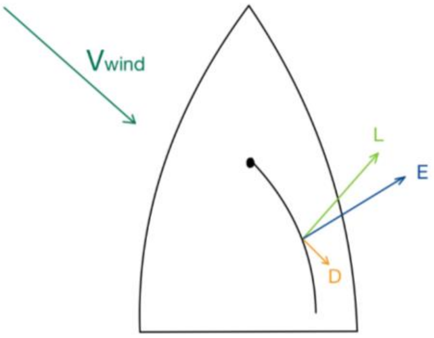


Figure 3: Forces acting on a boat's sail

The boat begins moving in the direction of this effort force. On the keel, which is an element that extends downwards from the hull's lower surface, the boat's increasing velocity is acting on it with an angle of attack, also generating a certain lift and drag force. Similarly, the rudder also generates these forces. The total force generated is called the resistance force, as seen in *Figure 4*.

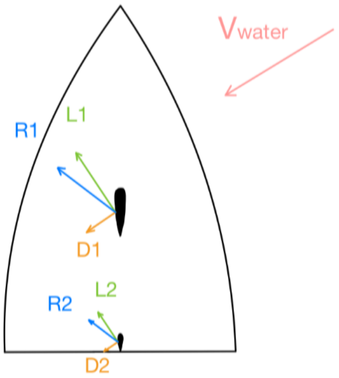


Figure 4: Forces acting on a boat's lower surface elements

When summing effort and resistance force, a final thrust force is obtained which propels the boat forwards and with a slight leeway, as seen in *Figure 5*. As the boat gains speed, the wind velocity that acts on the sail becomes the apparent wind velocity, which is the combination of the real wind velocity and the boat's speed. In the AC75s, which reach velocities of 50 knots way over the real wind's velocity, the apparent wind vector acts on the sails with a small angle of attack, as shown in *Figure 6*.

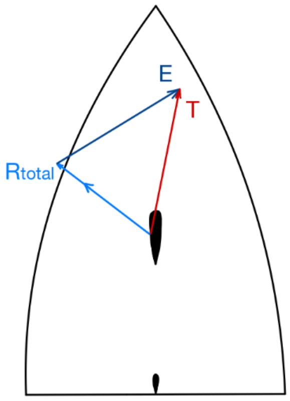


Figure 5: Boat thrust force generation

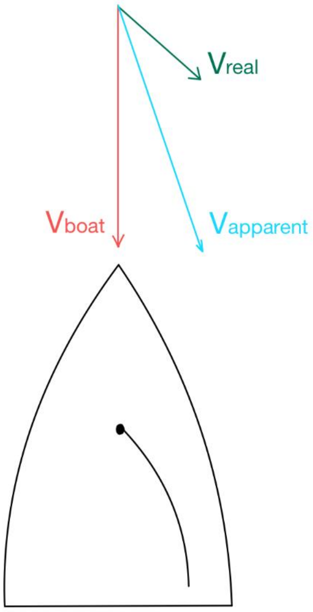


Figure 6: Apparent wind schematic

As it will be explained in *4.2. Foils*, the main difference between the AC75 and a conventional sailboat is that the keel is substituted by two separate foil wings, which on top of generating a resistance force, also generate a yawing moment.

One of the main design drives of the AC75 is the reduction of drag. Total drag is a combination of parasite and induced drag. While parasite drag is caused by friction between the fluid and the yacht, induced drag is a result of the generated lift force. The differential of pressure produced creates vortices at the ends of the wings, foils or any lifting element. The most effective way of limiting the effect of this induced drag is by increasing the wing's aspect ratio. The aspect ratio is a measure of how thin a wing is, and the higher it is, the more effective the lifting element will be. However, for a limited wing geometry, the introduction of a wing tip element can increase the effective wingspan, minimising induced drag by stopping the high pressure air from one side from going to the low pressure air of the other side. These winglets will be one of the most important aspects throughout the project.

CHAPTER 3. STUDY OF THE AC75 CLASS RULE

3.1. INTRODUCTION

The AC75 Class Rule is the document that describes all of the requirements and restrictions regarding the design, manufacturing and operation of the AC75. It's important to note that the Class Rule was slightly updated after the 36th America's Cup and, despite changes being minimal, it will be important to consider them when analysing the AC75s made using the previous Class Rule.

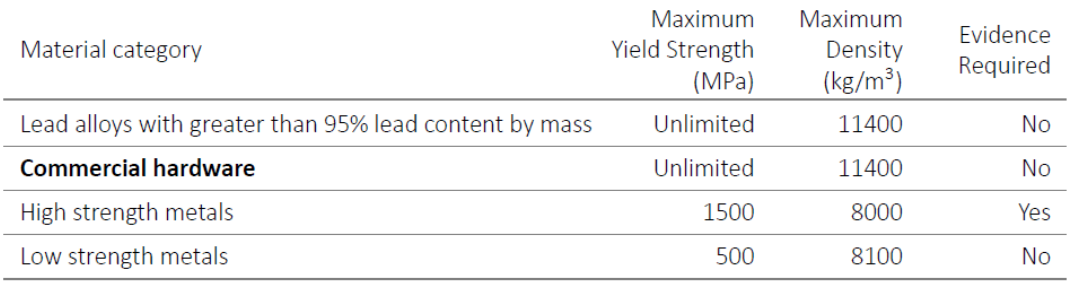
Although the Class Rule covers elements of the yacht such as surface finishes, hydraulic and electric systems, headsails, and crew, these are out of the scope of this project and will not be explored. Instead, focus will fall on materials, mass, hull, foils, rudder, mast and mainsail.

The most general rules state that the AC75 is a monohull yacht propelled by sails only. This has fomented a return to the more classical configuration of sailing yachts and a deviation from the modern catamaran or trimaran configurations. The AC75 consists of exactly one hull, two foils, one rudder, one mast, one mainsail and one jib. Another important general consideration to the AC75's design is that there are several supplied components. These include the mast, the foil cant arms, the rigging and the hydraulics.

3.2. MATERIALS

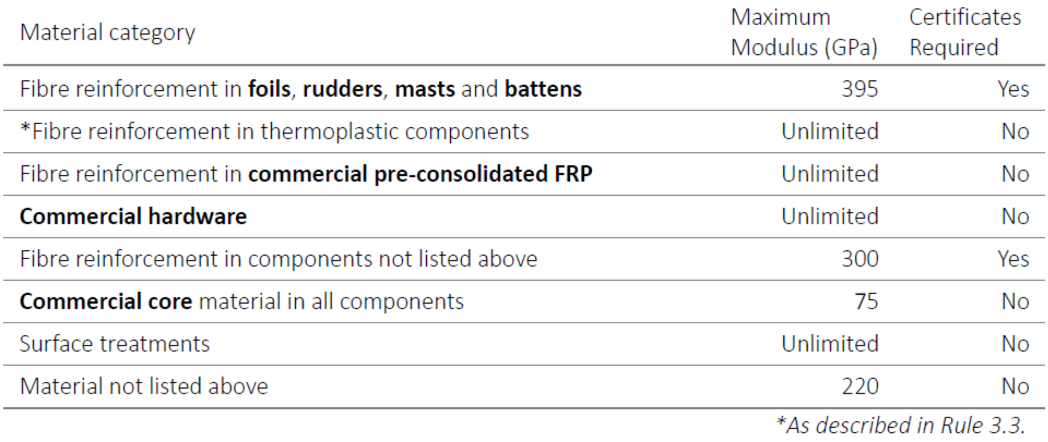
Available materials for the yacht's design are limited in terms of their properties, quantities and applications. In terms of their properties, no materials can exceed a density of 11,400 kg/m^3, which is close to the density value of lead and certainly bans most tungsten alloys and depleted uranium which are used for aerospace applications, specially in counterbalances for aeroelastic damping.

Additionally, metals located in the foil wings, foil flaps and in the rudders are further limited in their properties as shown in *Table 1*, and all materials must comply with *Table 2* with respect to their maximum elastic modulus.



Material category	Maximum Yield Strength (MPa)	Maximum Density (kg/m^3)	Evidence Required
Lead alloys with greater than 95% lead content by mass	Unlimited	11400	No
Commercial hardware	Unlimited	11400	No
High strength metals	1500	8000	Yes
Low strength metals	500	8100	No

Table 1: Maximum properties of metal materials located in foil wings, foil flaps and rudders [AC, 2022]



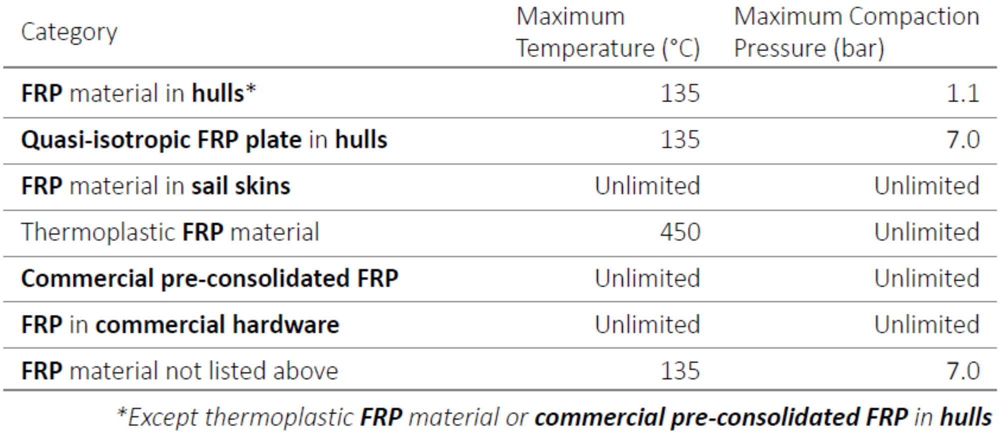
Material category	Maximum Modulus (GPa)	Certificates Required
Fibre reinforcement in **foils**, **rudders**, **masts** and **battens**	395	Yes
*Fibre reinforcement in thermoplastic components	Unlimited	No
Fibre reinforcement in **commercial pre-consolidated FRP**	Unlimited	No
Commercial hardware	Unlimited	No
Fibre reinforcement in components not listed above	300	Yes
Commercial core material in all components	75	No
Surface treatments	Unlimited	No
Material not listed above	220	No

**As described in Rule 3.3.*

Table 2: Maximum elastic modulus of all materials [AC, 2022]

Core materials used in sandwich structures such as in the yacht's hull will be limited to certain aluminium honeycombs, meta-aramid and para-aramid honeycombs, timber and plastic foam. An important consideration in this regard is that para-aramid honeycombs are not permitted in the hull shell below the perimeter line. Given that para-aramid honeycombs offer improved performance in weight, strength, stiffness and fatigue over their meta-aramid counterparts, it may be important to ensure that the perimeter line (located at the hull's maximum width and dividing the hull lower surface from the deck) is as low as possible without influencing aerodynamic efficiency, to take advantage of the para-aramid honeycomb's properties.

Finally, applied temperature and compaction pressure limitations are given for fibre reinforced polymer (FRP) materials in *Table 3*. Although these rules apply mostly to construction, it will be important to take them into account during design to ensure that the right FRP materials are being used in each part of the yacht.



Category	Maximum Temperature (°C)	Maximum Compaction Pressure (bar)
FRP material in **hulls***	135	1.1
Quasi-isotropic FRP plate in **hulls**	135	7.0
FRP material in **sail skins**	Unlimited	Unlimited
Thermoplastic **FRP** material	450	Unlimited
Commercial pre-consolidated FRP	Unlimited	Unlimited
FRP in **commercial hardware**	Unlimited	Unlimited
FRP material not listed above	135	7.0

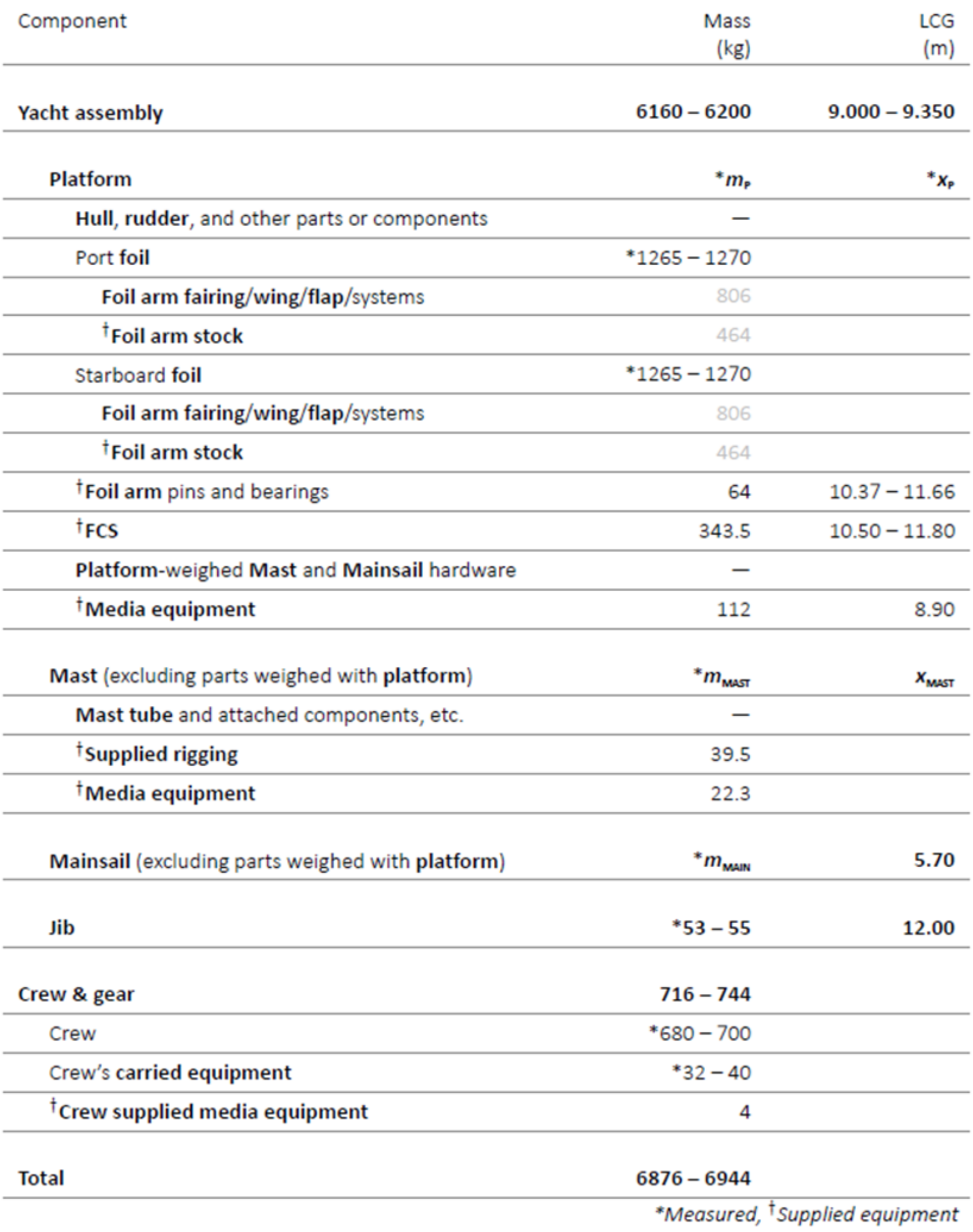
Except thermoplastic* ***FRP* *material or* ***commercial pre-consolidated FRP*** *in* ***hulls***

Table 3: Maximum applied temperatures and compaction pressures of FRP material [AC, 2022]

It's important to remark that commercial pre-consolidated FRP, as well as commercial hardware, is restricted to a maximum of 150 kg of the complete yacht and only 15 kg of the yacht's hull. Therefore, it will be essential to use this type of FRP efficiently.

3.4. MASS

The masses and longitudinal centres of gravity (LCGs) of most components of the AC75 yacht, as well as for the crew and the yacht itself, are restricted within a range as shown in *Table 4*. It will be important to analyse the effect that different LCG values within the given ranges will have, especially that of the complete yacht assembly.



Component	Mass (kg)	LCG (m)
Yacht assembly	**6160 – 6200**	**9.000 – 9.350**
Platform	*m_P	*x_P
Hull, **rudder**, and other parts or components	–	
Port **foil**	*1265 – 1270	
Foil arm fairing/wing/flap/systems	806	
†**Foil arm stock**	464	
Starboard **foil**	*1265 – 1270	
Foil arm fairing/wing/flap/systems	806	
†**Foil arm stock**	464	
†**Foil arm** pins and bearings	64	10.37 – 11.66
†**FCS**	343.5	10.50 – 11.80
Platform-weighed **Mast** and **Mainsail** hardware	–	
†**Media equipment**	112	8.90
Mast (excluding parts weighed with **platform**)	*m_{MAST}	x_{MAST}
Mast tube and attached components, etc.	–	
†**Supplied rigging**	39.5	
†**Media equipment**	22.3	
Mainsail (excluding parts weighed with **platform**)	*m_{MAIN}	**5.70**
Jib	***53 – 55**	**12.00**
Crew & gear	**716 – 744**	
Crew	*680 – 700	
Crew's **carried equipment**	*32 – 40	
†**Crew supplied media equipment**	4	
Total	**6876 – 6944**	

**Measured, †Supplied equipment*

Table 4: Mass and LCG ranges of the yacht's components and crew [AC, 2022]

3.5. GENERAL ARRANGEMENT

Many of the design rules make use of defined planes within the yacht's general arrangement. For example, there are restrictions on what can be located past certain planes or outside the projection of an element on a plane. This is the case of the hull lower surface, below which only the fairing flaps, foils and rudder can be found. Similarly, only the mast, sails, rigging, foils (when at their maximum cant angle) and media equipment shall be located 1.7 m above the measurement waterline plane (MWP) of the hull. This places a restriction on how low the perimeter line can be placed to take advantage of the para-aramid honeycomb. Therefore, a balance must be found between these two rules. Finally, no elements other than the mast, sails, foils, rudder and rigging may be located outside of the projection of the hull on the MWP, i.e. outside the perimeter line.

These rules create a complex and limited space in which elements can be located with respect to the yacht's hull. It will be essential to take these rules into account when designing the yacht.

3.6. HULL GEOMETRY

The hull must be a single closed volume and the rules regarding hull geometry constrain the longitudinal and transversal limits of the hull to ensure a balanced competition. Firstly, the aftmost point of the hull is located at the transom reference plane (TRP). Perpendicular to this plane is the longitudinal centre plane (LCP), which must also be the symmetry plane of the hull lower surface. The forward limit of the hull is located within a range of 20.6-20.7 m from the TRP.

Now that the longitudinal limits are established, the transversal limits are set using the perimeter line. It shall:

- be located entirely above the MWP
- have its furthest point from the LCP be located between 2.4 and 2.5 m from said plane
- be limited to 1.6 m from the LCP at its intersection with a plane 17 m from the TRP
- be limited to 1 m from the LCP at its intersection with a plane 19 m from the TRP

To make these rules clearer, *Figure 7* depicts the set longitudinal and transversal limits of the hull. Initially, it would seem preferable to reduce the cross section as much as possible, not only to reduce parasitic drag, but also to reduce the distance that the crew must travel to reach the opposite side of the yacht when tacking. The 0.1 m difference in the transversal limits is minimal, but every minimal detail must be taken advantage of to beat the competitors. Therefore, the 2.4 m limit will be preferable.

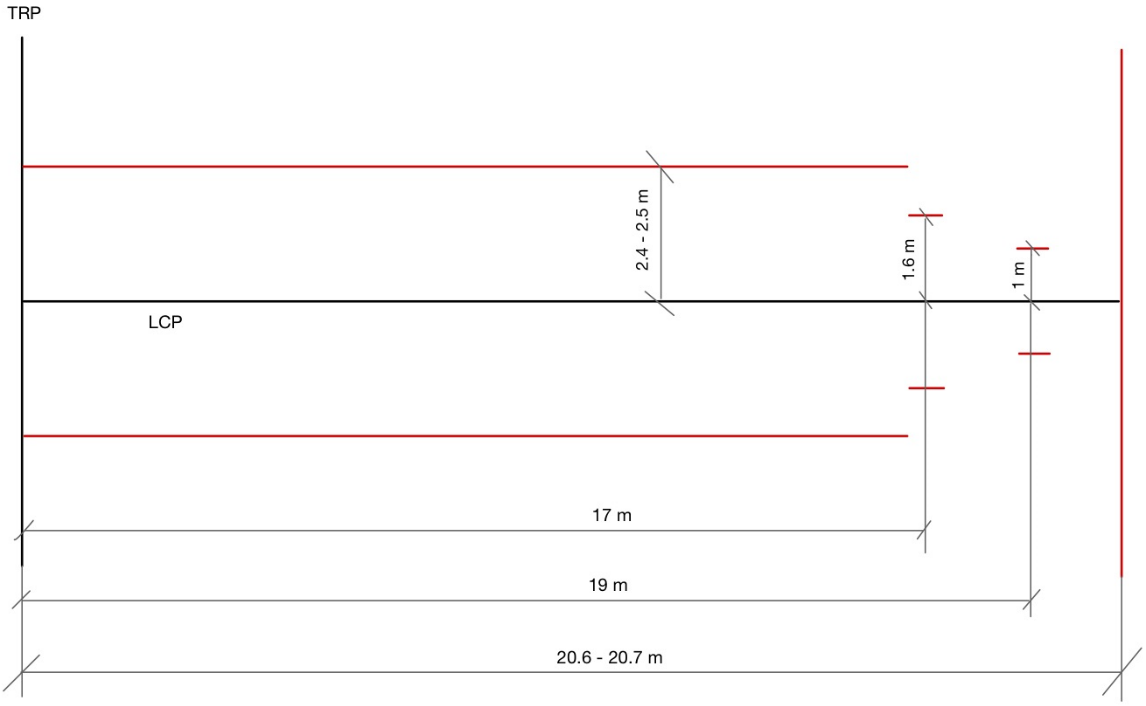


Figure 7: Hull geometry limitations

Other hull geometry rules include:

- the positioning of two watertight bulkheads, one at 9 m forwards of the TRP and the other between 17 and 19 m forwards of the TRP
- a minimum volume of 60 m^3 that the hull surface must enclose
- flotation rules
- the capacity for self-draining
- the inclusion of foil and rudder wet boxes, which are allowed to enclose a floodable volume of 300 and 30 litres respectively

- exceptions for penetrations in the hull surface which include conduit exits and drainage holes, which can both be covered using fairing flaps which have no purpose other than fairing the hull surface when water is not draining and preventing reverse flow

With respect to the hull structure, some restrictions are placed on the density of the hull shell. Particularly, the Rule states that no part of the hull shell shall have an areal density lower than 2 kg/m^3 and that the core used in the hull shell shall have a minimum nominal density of 48 kg/m^3.

3.7. FOILS

Two foils are found in the AC75, and each of them is made up of one foil arm, one foil wing, one foil flap and one or more foil systems, which shall be electrical, hydraulic or mechanical components used to connect the foil wing to the foil flap, connect segments of the foil flap, or provide information through sensors. It's important that these systems don't affect the hydrodynamic or aerodynamic forces significantly to ensure compliance with the Rule.

In terms of geometrical constraints for the foil, the foil itself must be located between planes located forwards of the TRP at 10 and 12 m. Additionally, the combination of foil wing and foil flap must fit within the foil wing box, which is defined in *Figure 8*. This box limits the span of the foil wing and it's important to note that the foil flap must fit within this box for all possible flap deflections.

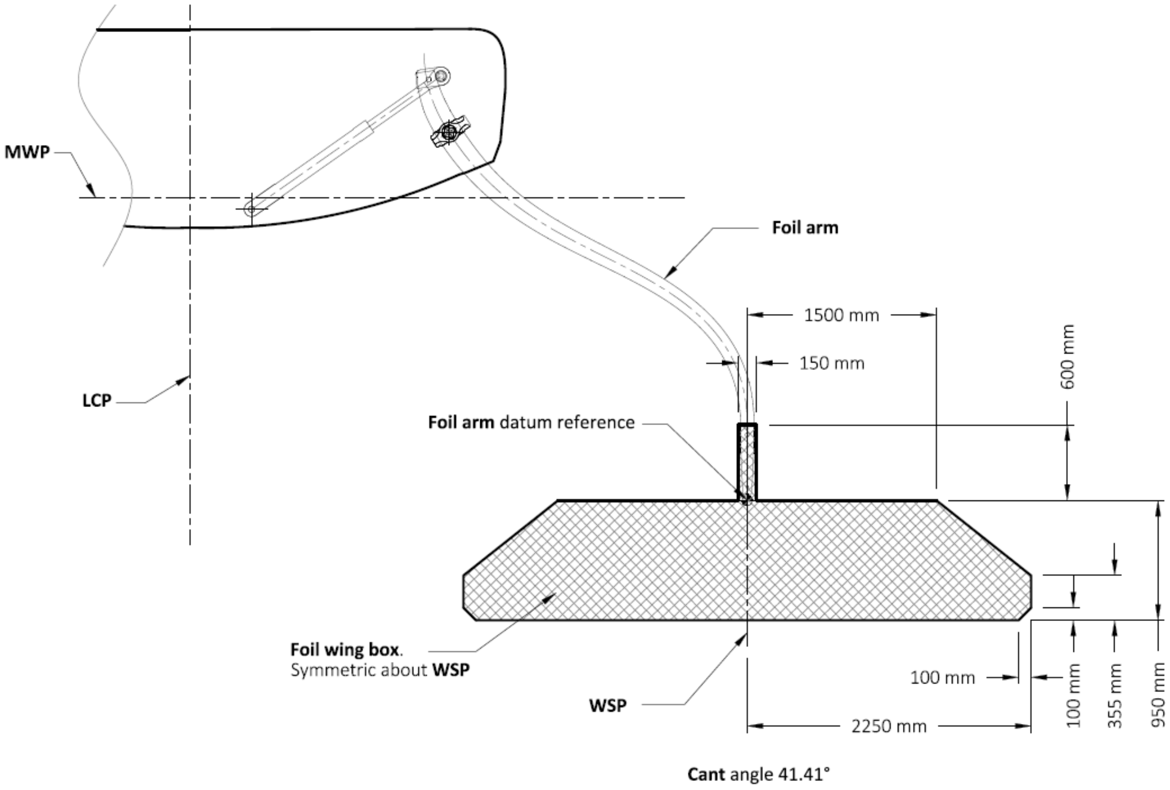


Figure 8: Foil wing box limitations [AC, 2022]

The foil may only rotate along its foil arm cant axis relative to the rest of the yacht, and no other movements are permitted. The cant angles that must be reached are from 7.6º to 119.5º. Nevertheless, the Rule just establishes these angles as a minimum. If some advantage is gained from reaching higher or lower angles, it may be interesting to adapt the design to that respect.

Additionally, some geometrical restrictions are given with respect to the foil cant system (FCS) and they can be found in *Figure 9*. This figure shows a cant angle of 7.5º. Despite this system being out of the scope of this project, the hull geometry may be determined by the position of the cant axes, which must be contained within the hull surface.

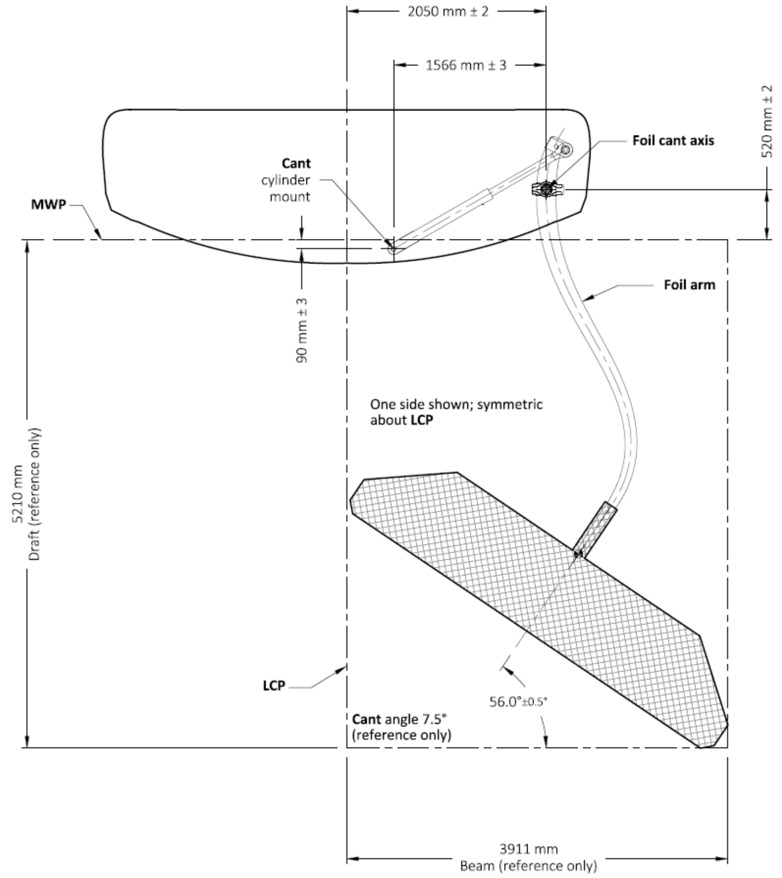


Figure 9: FCS constraints [AC, 2022]

The foil arms are one of the few provided elements, which can be covered using foil arm fairings. However, due to the lack of foil arm dimensions, they will not be modelled.

Both the foil wing and the foil flap must be symmetric about the wing symmetry plane (WSP) which can be identified in *Figure 3*. This includes all the flap segments which make up the foil flap. These symmetric constraints have a tolerance of 3 mm. Since there are no restrictions on the amount of flap segments, it will be important to analyse what amount of flap segments would be most convenient for operation of the yacht. The Rule also states that the chord length of the foil flap cannot be more than 50% of the chord length of the entire foil, and that the maximum rotation with respect to a central position around the hinge axis is ±45º. This doesn't define exactly what the "central position" is, so it will be possible to play with this rule in order to produce a larger downwash than what a deflection of 45º can provide.

3.8. RUDDER

The rudder of the AC75 englobes the vertical and horizontal stabilisers with their respective control surfaces. The Class Rule states various positional and geometrical constraints which refer specifically to the wetted part of the rudder. These include a symmetry constraint about the rudder centre plane and a longitudinal constraint which contains the rudder between the TRP and a plane 1.5m forward of the TRP. Additionally, the wetted part of the rudder must be contained transversally between two planes at 1.5m from the LCP towards both sides. Finally, the last 0.5m of the rudder (the lowest part) must have a minimum area of 0.3m^2 when projected onto the MWP.

The rudder can only touch the hull lower surface, a lower bearing which provides rake (the equivalent to pitch in an aircraft), and a higher bearing which provides yaw. Both of these bearing centres must be separated vertically by a minimum distance of 600mm. No other movements apart from rake and yaw are permitted for the rudder.

3.9. MAST

The mast is the structure that will hold the sails in the vertical direction. It's a provided element but a fairing must be placed over it. The aft face of the mast must be straight within a tolerance of ±10mm along the length of the mast. The openings that this aft face can have are detailed in the Class Rule.

Additionally, Rule 15.11 describes how far aft or forward can certain elements belonging to the mast be found. Two of the most important areas in this regard are the mast lower zone, which extends 7.8m aft of the aft face of the mast and 1.5m upwards from the deck; and the area within 0.3m of the mast upper plane, which extends from 100mm aft to 20mm forward. The mast lower zone allows teams to consider the addition of a boom, a longitudinal beam that can rotate around the mast's axis and which holds the mainsail's base. A study into the necessity of this element will be done in the preliminary design of the mainsail. Finally, it's important to note that the mast has a rake angle of 5º, as shown in *Figure 10*, which also places the mast's base and longitudinal location.

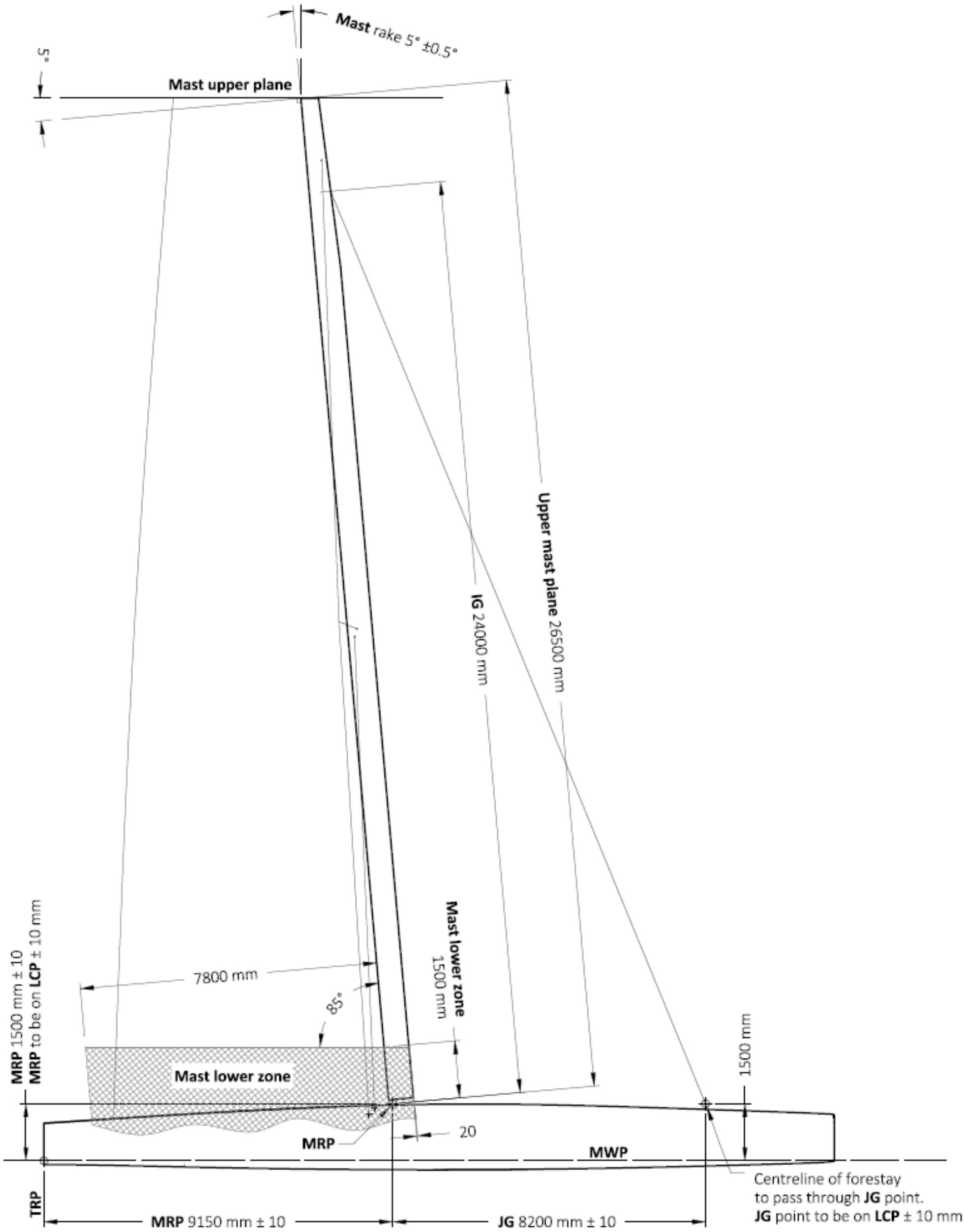


Figure 10: Rig Plan [AC, 2022]

3.10. MAINSAIL

The mainsail is made up of two sail skins which together form a symmetrical airfoil shape initially, but as the mast rotates a cambered airfoil shape is created instead. This allows for maximum efficiency on any of the yacht's possible courses.

Having analysed this Class Rule, it's the designer's conclusion that the rules concerning the mainsail are some of the most open to interpretation. This is due to the fact that at no point of the Rule is the use of wing tip devices explicitly prohibited, but there are several rules which put obstacles on the design of this element.

These rules include the definition of the elements that make up the mainsail, in which a wing tip device may be camouflaged as one of the permitted fairings or even as the sail skins themselves. Another rule describes the nature of these permitted fairings, which include one with the only purpose of sealing the space between both sail skins near the sail's highest point. The mainsail's preliminary design will explore possible interpretations of these rules that can allow for the addition of a wing tip device.

Additionally, the Rule describes dimensions of possible sail skin openings which function as access panels, the locations of sail skin reinforcements, and more importantly the dimensions, quantity and location of battens. Battens are 75mm in diameter longitudinal elements which shape the sail and give it structural integrity. Several battens are placed along the mainsail's span.

Differently to other editions of the America's Cup, the sail of the AC75 must be capable of being raised and lowered. To achieve this, they must have a continuous attachment to the mast in the form of a rail in each sail skin until 100mm under the head point. *Figure 11* shows the position of this head point as well as the spanwise dimension limitation, and *Table 5* contains the chord or girth limitations.

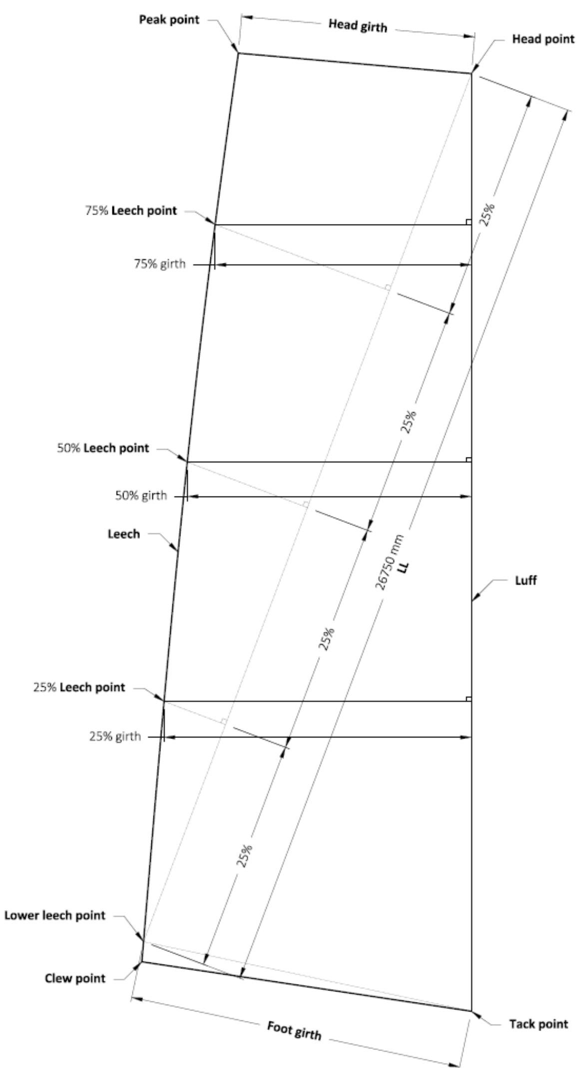
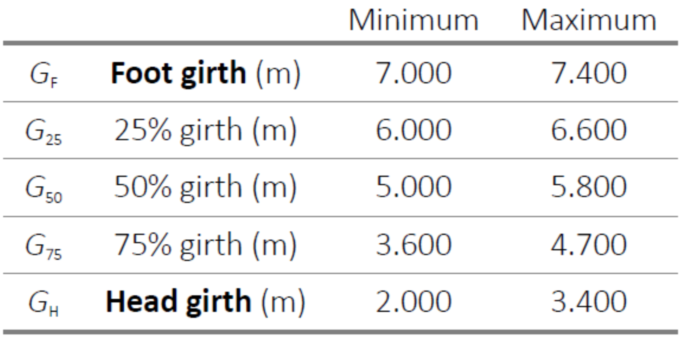


Figure 11: Mainsail Plan [AC, 2022]



		Minimum	Maximum
G_F	**Foot girth** (m)	7.000	7.400
G_{25}	25% girth (m)	6.000	6.600
G_{50}	50% girth (m)	5.000	5.800
G_{75}	75% girth (m)	3.600	4.700
G_H	**Head girth** (m)	2.000	3.400

Table 5: Mainsail girths [AC, 2022]

CHAPTER 4: PRELIMINARY DESIGN

4.1. HULL

4.1.1. COMMON FEATURES & DESIGN FOCUS

One of the elements which varies most between all four of the 36th America's Cup competitors is the hull. *Figure 12* shows a comparison between the hulls, from which it's possible to extract some common features and main differences.

Figure 12: AC75 hulls (ETNZ top left, LRPP top right, AM bottom left, IB bottom right)

The most important characteristic that can be found across all four competitors is a keel-like element at the hull's lower surface. Although varying in size and extension, all four boats have some thin, longitudinal element at the lowest point of the hull's surface. While less prominent in American Magic and clearer in Ineos Britannia, the objective of this element is to prevent the generation of vortexes below the hull's surface, which would increase induced drag. Similarly to a wing's winglet, this hull element prevents the high pressure air from one side of the mainsail from travelling to the low pressure side. However, for this to work, it's essential that the yacht flies as low as possible so as to break the flow of air between both sides. Therefore, it's important that, in case of hitting a wave or having a "touch-down", the wetted area of this element is as small as possible to reduce drag.

Another important function that this element performs is to help the boat through its acceleration phase and make it easier to take-off at certain high speeds [Fischer, 2020] [Ainslie, 2020]. Presumably, what this keel-like element or “bustle”, as teams call it, would do is break the suction effect generated on take-off from the water’s surface. A completely flat and large surface would pose a much bigger challenge in this regard.

In the particular case of American Magic’s hull, which has very little volume at the back, the design intent is to be able to take-off the stern easier, whereas the other teams require going slightly “down on the nose itself” to clear this part of the hull from the water’s surface [Muyl, 2020]. However, the amount of induced drag generated under that section of the hull is too large, and because there is a minimum required weight for the complete hull, this decision results in an excessively large volume at the hull’s bow.

Consequently, the design focus for the hull’s preliminary design will follow more closely the design of the other three competitors, particularly Ineos Britannia, with a pronounced bustle and very smooth curves. Moreover, a design with a lower perimeter line will be considered in order to take advantage of the para-aramid honeycomb material rule found in the AC75 Class Rule (see *3.2. Materials*).

4.1.2. PRELIMINARY DESIGN

Figure 13 shows the two possible hull cross section preliminary design options:

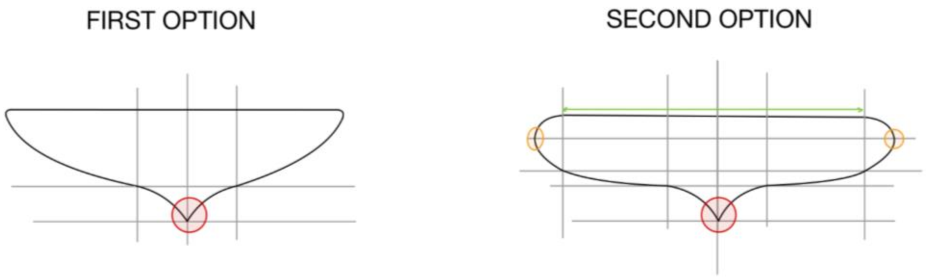


Figure 13: Hull preliminary design options

Both options have a bustle, which would extend longitudinally throughout the entire hull. The difference is found in the position of the perimeter line, which is also the widest cross section of the hull, and which separates the deck from the hull's lower surface. The lower location of the perimeter line in the second option brings two different advantages. Firstly, a larger percentage of the hull's structure will be able to use a stronger material, which would improve the yacht's possibilities of surviving a crash and would make sailors more inclined to find the limits of the yacht during training and testing without fear of destroying the hull. Secondly, cockpits could be positioned further towards the centre of the boat, reducing the distance that sailors must travel to change from one side to the other during manoeuvres. This would save time and may result in a large advantage during a long race.

On the other hand, the Class Rule is strict when it comes to floatability and this perimeter line positioning may negatively affect buoyancy. Therefore, a balance between the two designs may be the safest option for a final design, but it would nevertheless be interesting to evaluate the true benefits of the second option on a testing boat.

Figure 14 shows the preliminary design of the hull's cross section:

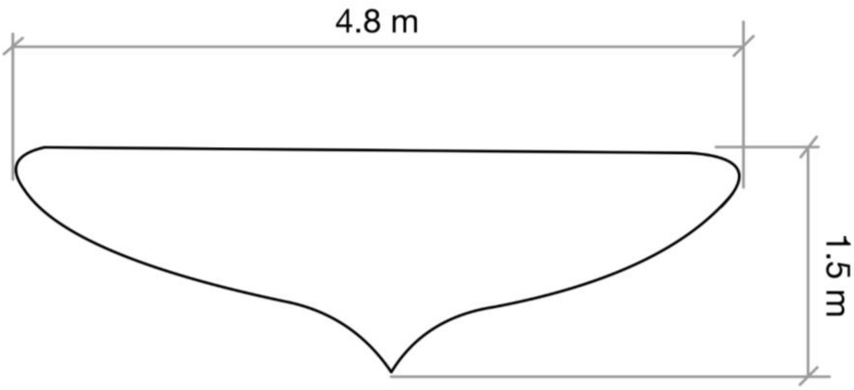


Figure 14: Hull cross section preliminary design

4.2. FOILS

4.2.1. COMMON FEATURES & FIRST DESIGN

Through an initial analysis of all competitors during the 36th America's Cup, some common features were found with respect to foil design. These common characteristics include:

1. Negative dihedral: Despite being detrimental to stability in aircraft, which contrarily make use of positive dihedral, almost all AC75s have a negative dihedral angle in their foils. Possible reasons for this characteristic are the wing box dimensions shown in *Figure 3,* which favour a larger foil span for negative dihedral foils than for positive dihedral ones. However, some teams have much less dihedral than others, especially ETNZ. It will be essential to fully understand this feature of the foils in order to design a successful AC75.
2. Foil flap segments: Most teams have decided to install just two foil flap segments per foil flap, one at each side of the WSP. Although it's almost impossible to see what happens underwater, there is a possibility that both these flap segments work in unison, meaning that no flap segment is deflected while the other isn't. Doing this greatly simplifies the operation of the AC75 and is a characteristic that will definitely be implemented in this design.
3. Wing tip devices: All teams make use of wing tip devices to reduce induced drag of the foil wing. All of them are similar to the blended winglets used in modern commercial aircraft, but at the same time each of them has different shapes and approaches. *Figure 15* shows the winglets used by each team.
4. Ballast at foil wing centre: As shown in *Table 4*, each foil must weigh more than ⅙ of the yacht's total mass, which for most teams was solved with the use of a ballast in the foil wing. It is the designer's belief that this ballast is located at the centre of the foil wing, with an ellipsoid's shape, as shown in *Figure 16*. When looking at ETNZ's smaller foil wing size with respect to the other teams, it makes sense that its ballast is larger, to compensate for the required mass. This ballast will help ensure that the yacht doesn't capsize.

Figure 15: Foil winglets (ETNZ top left, LRPP top right, IB bottom left, AM bottom right)

Figure 16: Foil ballast (ETNZ top left, LRPP top right, AM bottom left, IB bottom right)

There is one particular foil wing which is completely different to the rest, that of ETNZ. It is the foil wing with the least negative dihedral and additionally it has the least wing area. Curiously, it’s also the foil wing of the 36th America’s Cup winner. Whether this foil wing design is what granted ETNZ their victory is almost impossible to tell. Nevertheless, it could be an interesting analysis.

The following figures represent the first designs for the foils inside the foil wing box. Note that the design would be symmetric about the WSP. Foil Design #1 has a similar configuration to that of the Challengers during the 36th America's Cup, while Foil Design #2 has a slight positive dihedral angle, which none of the competitors had, to understand its effect on the yacht through analysis. Both of these foil designs have two foil flap segments, and the chord and foil cross section have not yet been decided.

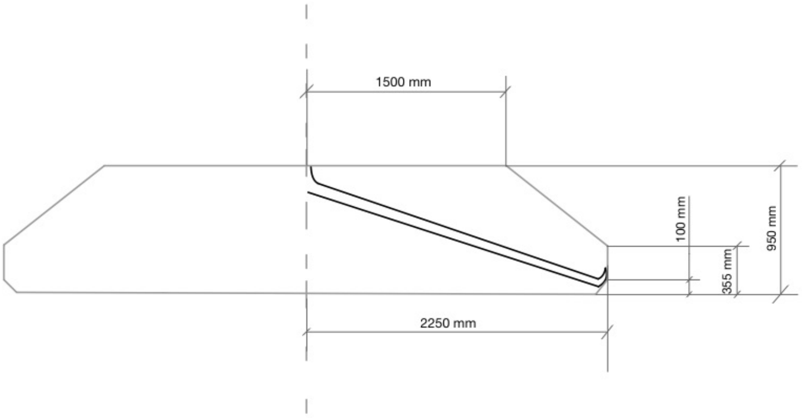


Figure 17: Foil Design #1

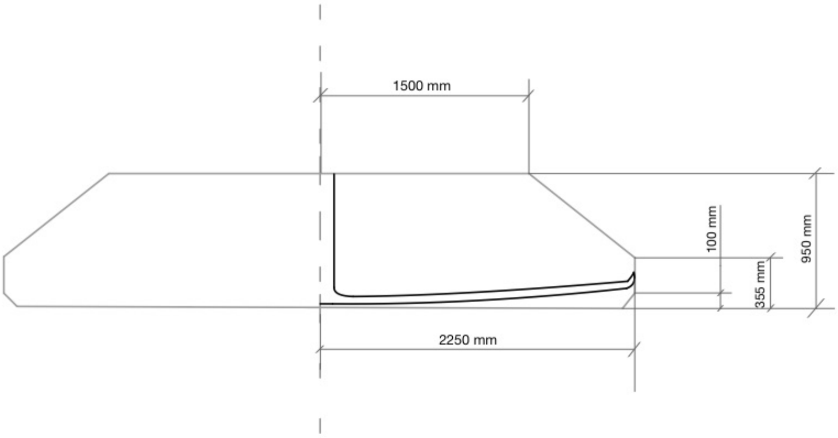


Figure 18: Foil Design #2

4.2.2. UNDERSTANDING NEGATIVE DIHEDRAL & THE MULTIPLE ROLES OF THE FOIL WINGS

A meeting with the project supervisor about the reasoning behind the negative dihedral feature found in most AC75 foils gave great insight not only into this particular feature, but also the roles that the foils play apart from providing lift.

The AC75 lacks a particular limb that most conventional sailing boats have: the keel. The keel is a symmetrical "wing" which extends from under the boat's hull and which occasionally has a heavy bulkhead at the bottom, and it has the purpose of providing the resistance force necessary to generate thrust and a righting moment whenever the boat heels (see *2.2. Theoretical Background*). The buoyancy of the sailboat's hull also contributes to this righting moment. Given that the AC75's hull is not in contact with the water's surface while flying and that it has no keel, this role falls on the foils.

The foils produce this righting moment in two different ways: through the weight of the lifted windward foil and through a component of the lift generated by the leeward foil (see *Figure 19*). Note that there are other factors that affect these heeling moments such as the water's resistance to them and the foil cant angle.

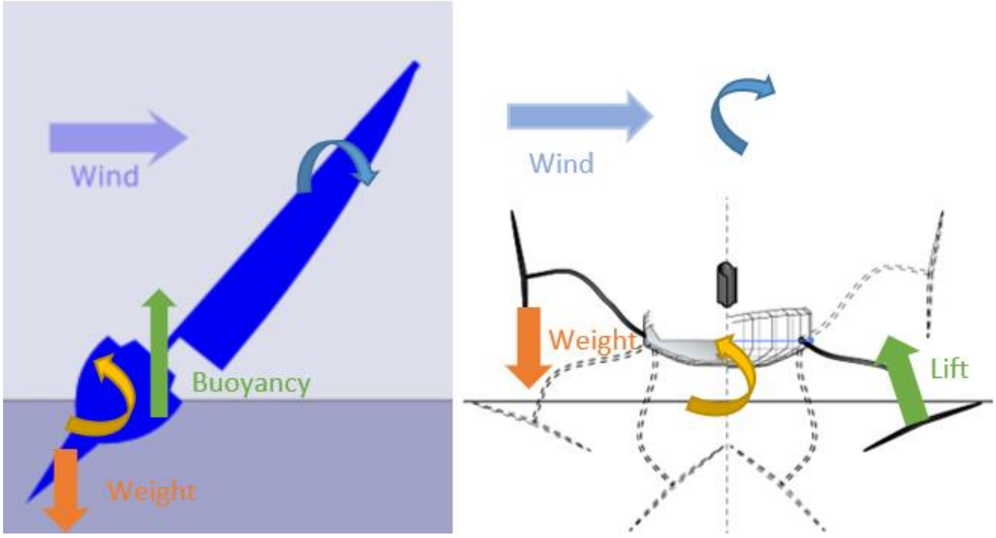


Figure 19: Righting moment production in conventional sailboats (left) vs the AC75 (right)

Better understanding the roles of the foil wings, it becomes clearer why a negative dihedral is preferred:

- Due to the foil wing box constraints, it's one of the options which provides the most span length, increasing wing area and therefore lift.
- Whereas the entire foil wing area is required to lift the yacht out of the water, when the yacht is flying this large amount of lift is no longer required. Therefore, the foil wing is lifted to a position as close as possible to the water's surface, where the drag produced by the foil arm will be minimal, as shown in *Figure 20*. At this position (Position 1):
    - It's expected that the righting moment will be equivalent to that of Position 2 $(M = Lz_1 * y_1 - Ly_1 * z_1 \simeq Lz_2 * y_2)$
    - Windward force will increase, which will allow the yacht to sail in a course that brings it closer to the buoy, limiting the amount of tacks necessary.
    - A foil wing with negative dihedral will reduce the amount of foil arm inside the water, further decreasing drag (see *Figure 21*).
- On the other hand, Foil Design #2, shown in *Figure 18*, would suffer from structural problems since the foil arm would have to be extended, and the amount of foil arm inside the water would be larger, increasing drag.
- The instability that negative dihedral wings would provoke on an aircraft is not applicable to this case due to scale and manoeuvrability of the foil arms.

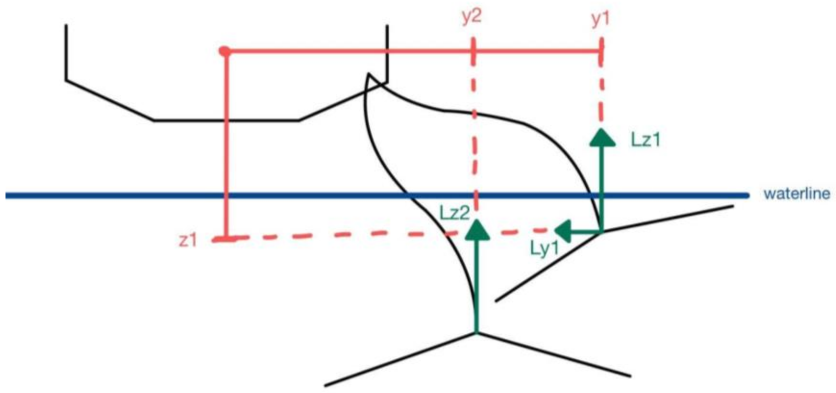


Figure 20: Forces study of foil arm positions

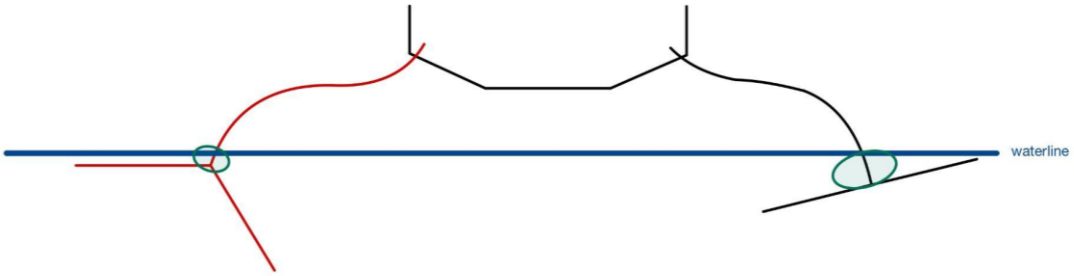


Figure 21: Underwater foil arm section for negative dihedral foil (left) vs no dihedral foil (right)

All this information directs the final design further towards a negative dihedral configuration, as seen in *Foil Design #3* (*Figure 22*), which was designed using CATIA to allow for easy editing of the foil shape, dimensions and position. Note that the central bulkhead has not yet been defined, and that chord is largely reduced at the tip to decrease induced drag. The design fits perfectly within the foil wing box and complies with the longitudinal restrictions.

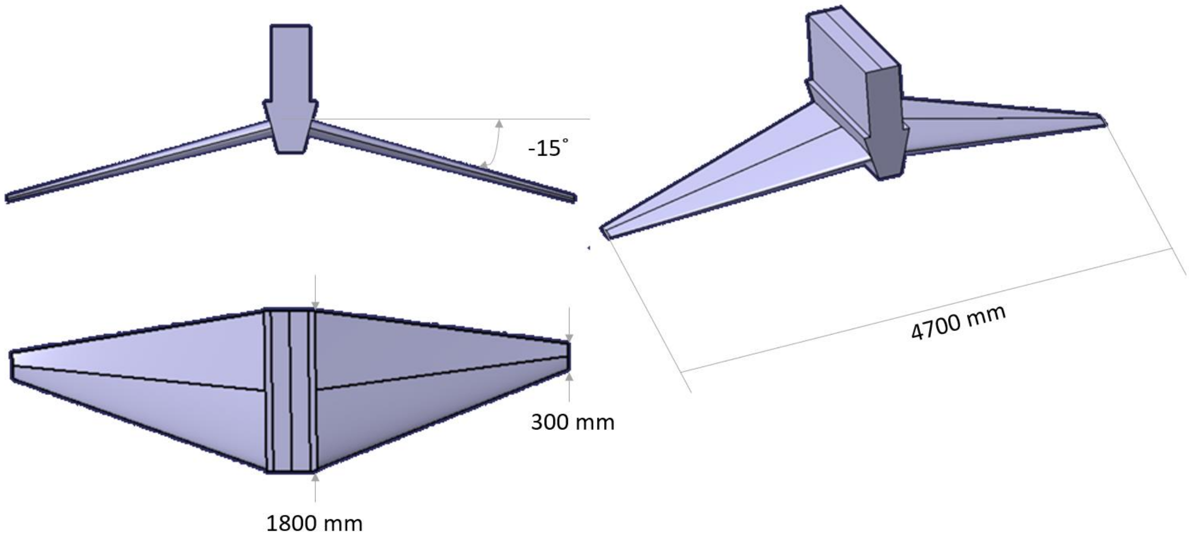


Figure 22: Foil Design #3

Finally, in terms of the longitudinal position of the foil wings, two aspects must be taken into account. Firstly, the position of the foil will affect the yacht's true rolling axis. *Figure 23* shows how this axis, which would be fully longitudinal in any conventional ship, extends from the rudder to the foil wing. The further aft the foil is located, the more inclined this axis will be, and the more complex it will become for the crew to operate. On the other hand, considering that the yacht's longitudinal centre of gravity must be located between 9m and 9.35m from the TRP, and that the foil must be positioned between 10m and 12m from the TRP, locating the foil as forward as possible translates into a yawing moment produced by the resistance force as shown in *Figure 24*. This would imply a constant deflection of the rudder to compensate for this yawing moment. Assuming an excellent sailing ability from the crew, and with the objective of reducing drag as much as possible, the decision for this design will be to place the foil as close as possible to the 10m limit, i.e. the aftmost point. However, testing could provide further information as to the difficulty that this decision poses to the crew.

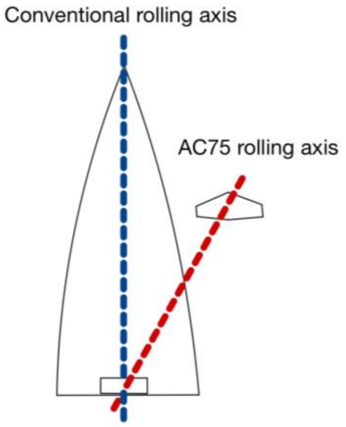


Figure 23: Rolling axis displacement

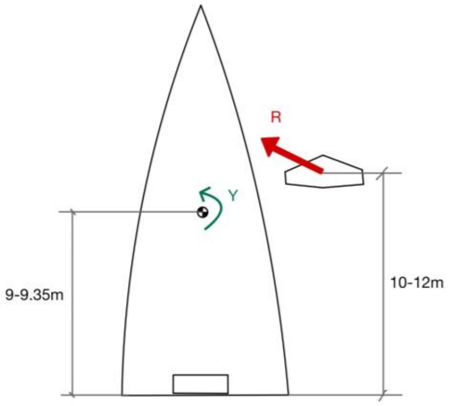


Figure 24: Yawing moment generation due to foil resistance force

4.3. RUDDER

4.3.1. COMMON FEATURES

The rudder works as a vertical and horizontal stabiliser, and contains two control surfaces in the form of a conventional rudder and an elevator. Despite there not being many images available from most competitors' rudders other than those of their test boats, *Figure 25* shows a great comparison between ETNZ and American Magic's rudders.

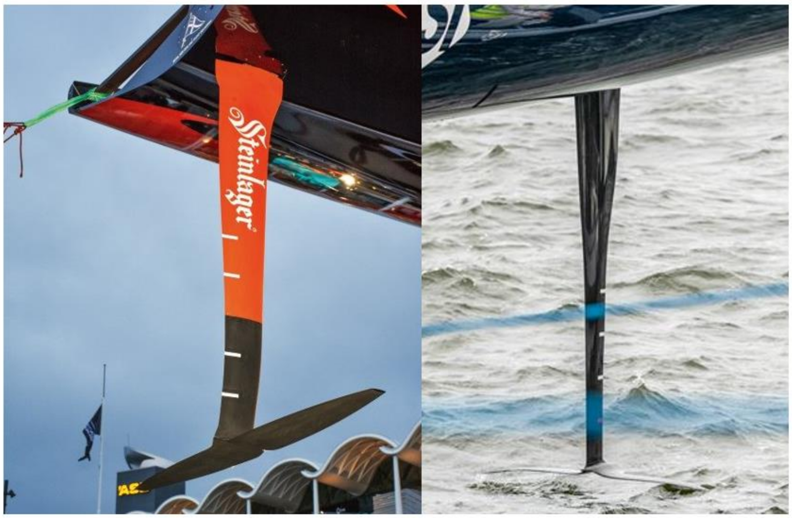


Figure 25: AC75 rudder comparison (ETNZ left, AM right)

It can be appreciated that both rudders have a slight reduction in chord on the vertical stabiliser element as it progresses downwards. This chord length seems to be very similar between both rudders, and is probably the minimal chord length in which the hydraulic lines and actuators from both the rudder and elevator are able to fit.

Looking at the horizontal stabiliser element of the rudder, it's possible to see an elliptical shape in ETNZ's rudder. This is the theoretically most efficient wing shape, which is usually sacrificed in conventional aircraft due to its complicated manufacturing, but in this case it may be the best possible option. American Magic's wing shape can't be fully appreciated, but it's possible that they have also gone for an elliptical shape given that they had already employed it in their test boat, as seen in *Figure 26*.

Figure 26: Elliptical horizontal stabiliser element in American Magic's test boat's rudder

One final important common feature is that the foil sections of the complete rudder are very thin. Considering that a symmetric airfoil must be used, a possible NACA airfoil could be the 0007.

4.3.2. PRELIMINARY DESIGN

The preliminary design of the rudder will include the previously mentioned characteristics, including the elliptical elevator. Given that no rule specifies the downwards extension of the rudder, the elevator will be positioned at the same depth as the foil at approximately 2.5 m from the MWP. This will ensure that no matter how high the foils lift the yacht, the crew will have both yaw and rake control up to the point where the foil itself leaves the water's surface.

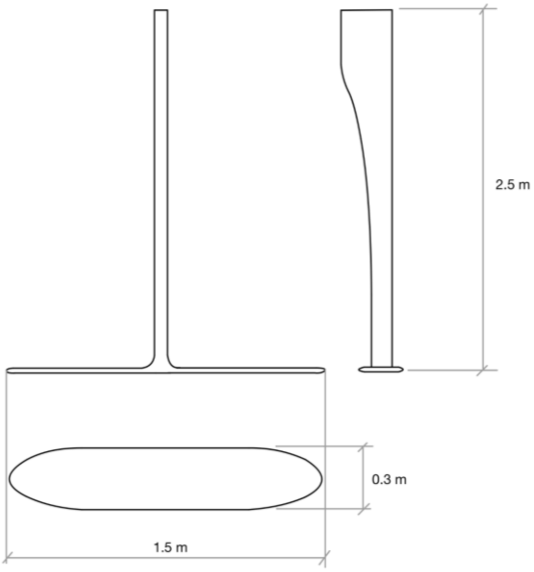


Figure 27: Rudder preliminary design

4.4. MAINSAIL

4.4.1. COMMON FEATURES

The most interesting aspect when comparing the 36th America’s Cup competitors in terms of their mainsail is the lower area. Conventional sailboats have always employed what is called a “boom”, which is a longitudinal structure attached to the mast and which rotates around it, supporting the base of the mainsail. However, when it comes to the AC75s, some teams came up with a way to endplate the space between the sail and the deck, which is a source of induced drag. *Figure 28* compares the four competitors.

Figure 28: Mainsail base comparison (ETNZ top left, LRPP top right, AM bottom left, IB bottom right)

As it can be appreciated, both ETNZ and Luna Rossa opted for a boomless design, in which all of the rigging is found under the deck and the clew point of the mainsail is connected to a rail which moves it from port to starboard in order to achieve the necessary angle of attack throughout the mainsail. On the other hand, American Magic and Ineos Britannia used a boom to support the mainsail’s base. Despite having the downside of generating induced drag, this design can more easily translate the desired wing shape throughout the entire lower area of the mainsail. This is because the boom supports the entire foot of the mainsail instead of just the clew point. In fact, it’s speculated that in order to translate the wing shape throughout Luna Rossa’s lower mainsail, a hydraulic ram is used, which forces the sail skins on a certain shape

[Morris, 2021]. Nevertheless, the designer is more inclined towards the boomless design, given that it comes with the added benefit of being able to have a smoother deck surface.

The twin sail skin concept of the AC75 is a complicated system in which, in order to transform the wing shape to a certain camber, the leeward skin is tensed while the windward skin is left loose. To make sure that both skins are tense and ensure the smoothest possible wing shape, some teams have opted for a solution in which a hinge is located at approximately ⅓ of the chord and on the head of the mainsail. This hinge rotates in order to translate this tension, as it can be observed in *Figure 29*.

Figure 29: Mechanism at mainsail's head to apply tension on both sail skins

4.4.2. WINGLET DESIGN OPTIONS

One of the unique features of this preliminary mainsail design is the addition of a wing tip device or winglet at the mainsail's head. As explained in *3.10. Mainsail*, one of the possible

Class Rule interpretations that would permit the creation of a wing tip device is the definition of one of the permitted fairings, which has the objective of covering the space between sail skins at the mainsail's head. Due to the fact that a winglet works equally no matter the yacht's course, this option is very plausible.

Another possibility in case this rule interpretation is not accepted, involves the creation of a support structure which extends towards one side from the mast, through which one of the sail skin's rails extends, forcing the skin to adopt the winglet's shape. Then, both sail skins can be connected with the aforementioned fairing and the winglet would be created. However, it would be more complicated to translate this shape along the mainsail's head chord. This second design option is shown in *Figure 30*.

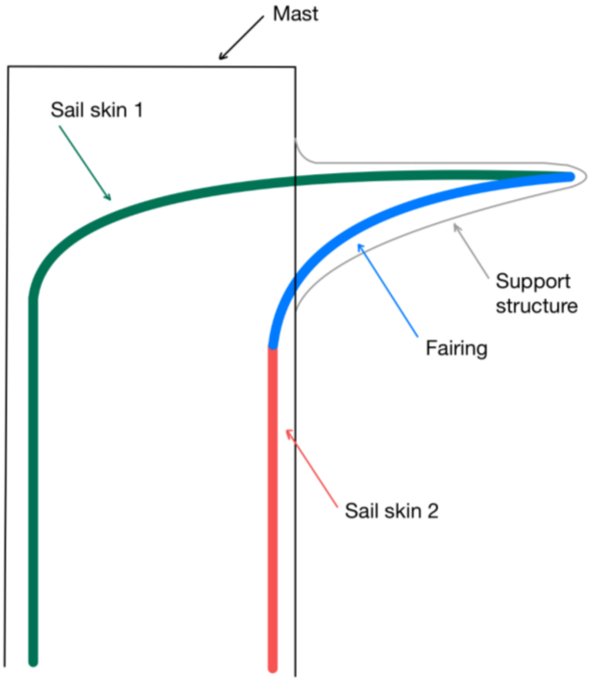


Figure 30: Alternative mainsail winglet proposal

To evaluate the plausibility of a winglet element on the mainsail, a meeting was set with Nicolas Bailey, current Foil Designer for Alinghi Red Bull Racing, one of the 37th America's Cup teams. Nicolas remarked that he didn't recall this idea being mentioned previously in the team, but that as long as the Class Rule didn't prohibit it, it was a very plausible idea. He mentioned, however, that one of the downsides that the use of a wing tip device may have is that it will raise the centre of pressure in the mainsail. To compensate for this effect as much as possible, mainsail girths close to the head will be closer to their minimal value, while the girths closer to the foot will be maximised within the limits of the Class Rule. The preliminary mainsail design is shown in *Figure 31*:

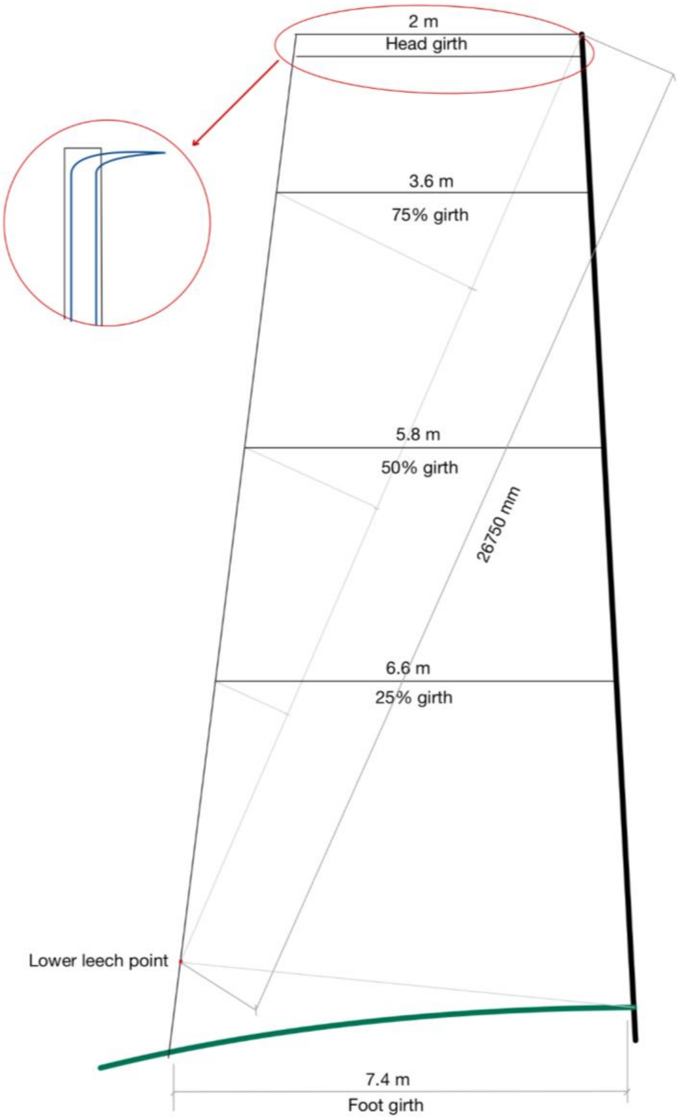


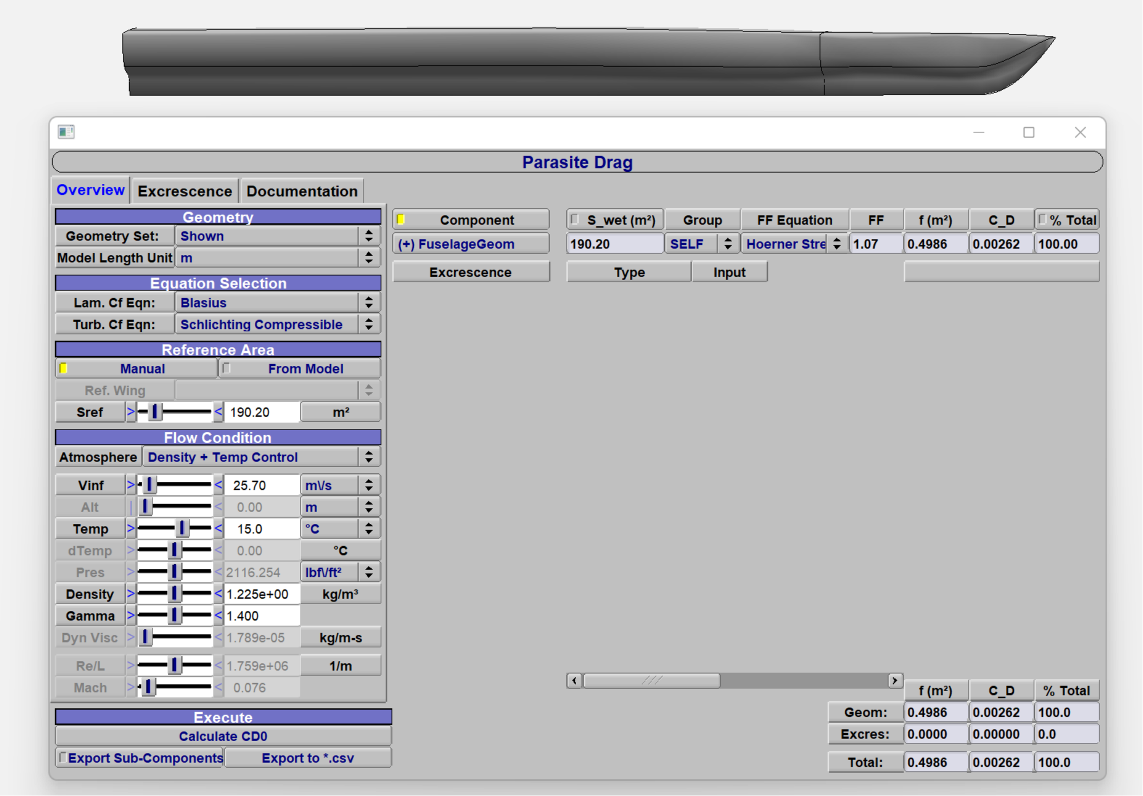
Figure 31: Mainsail Preliminary Design

CHAPTER 5. ANALYSIS

5.1. HULL

By taking the preliminary design hull section shown in *Figure 14* and extending it within the Class Rule's set dimensions, it's possible to perform a parasitic drag analysis on the resulting hull. This analysis will be performed for the configuration in which the yacht reaches its maximum speed of 50 knots and is foiling over the water.

The analysis was performed using OpenVSP's parasitic drag calculation tool, as seen in *Figure 32*:



Geometry Set: Shown
Model Length Unit: m
Lam. Cf Eqn: Blasius
Turb. Cf Eqn: Schlichting Compressible
● Manual ☐ From Model
Ref. Wing
Sref: 190.20 m²
Atmosphere: Density + Temp Control
Vinf: 25.70 m\/s
Alt: 0.00 m
Temp: 15.0 °C
dTemp: 0.00 °C
Pres: 2116.254 lbf\/ft²
Density: 1.225e+00 kg/m³
Gamma: 1.400
Dyn Visc: 1.789e-05 kg/m-s
Re/L: 1.759e+06 1/m
Mach: 0.076

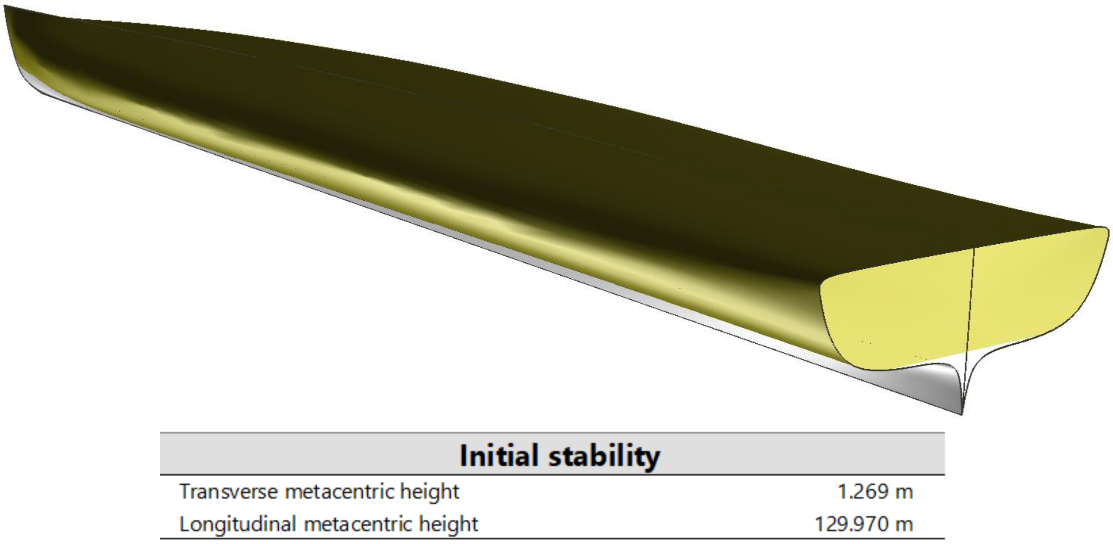
Component	S_wet (m²)	Group	FF Equation	FF	f (m²)	C_D	% Total
(+) FuselageGeom	190.20	SELF	Hoerner Stre	1.07	0.4986	0.00262	100.00

	f (m²)	C_D	% Total
Geom:	0.4986	0.00262	100.0
Excres:	0.0000	0.00000	0.0
Total:	0.4986	0.00262	100.0

Figure 32: Parasitic drag calculation of the hull's preliminary design

The results show a parasitic drag coefficient of 2.62e-03, which is perfectly acceptable and shows great potential for this hull design.

Additionally, in order to evaluate the hull's stability while floating on the water's surface, a hydrostatics analysis will be performed using the DelftShip software. To do this, the ship was imported onto DelftShip and the analysis was run. The complete hydrostatics report can be found in *Annex I*, but *Figure 33* shows the most important information related to initial stability.



Initial stability	
Transverse metacentric height	1.269 m
Longitudinal metacentric height	129.970 m

Figure 33: AC75 Hull model on DelftShip software and initial stability information from hydrostatics report

This information is quite favourable, since one of the criteria that makes a ship seaworthy is that the metacentric height is higher than 0.15 m [Chopra, 2019]. A transverse metacentric height of 1.269 ensures that the yacht is very stable. Longitudinally, the yacht recovers from any disturbance due to waves or other elements almost immediately. If this were to be a passenger ship it would be important to consider that this rapid recovery may negatively affect the passengers' state after prolonged periods of time. However, considering that this is a racing yacht, this extra stability will be appreciated and will contribute to the righting moment.

5.2. FOILS

5.2.1. PRELIMINARY DESIGN ANALYSIS & OPTIMIZATION

Having come up with the preliminary foil design shown in *Figure 22*, the next step would involve understanding what results are required from the foil to be able to compete at the maximum level. Initial thoughts in this optimization process focused on producing enough lift force to lift the yacht out of the water at low speeds of 15 knots, resembling competitors. However, it became clear that producing such an amount of lift with no flap deflection at low speeds would involve producing exceeding amounts of lift at high speeds, which would require the flap to be deflected upwards to avoid the yacht from lifting off the water's surface.

Instead, the correct focus of this optimization process falls on producing a lift force equivalent to the yacht's weight at high speeds of 50 knots, which is where no flap deflection, and therefore minimum drag, is preferred.

With this objective in mind, a low thickness and low camber airfoil was designed, parting from the NACA 1108 on the xflr5 software and obtaining an 11.54% reduction in drag at very low angles of attack as seen in *Figure 35*. This airfoil shape was obtained through manual iterations until a satisfactory result was obtained. *Annex II* shows the results of said iterations. The low thickness and low camber of the airfoil is intended to decrease drag.

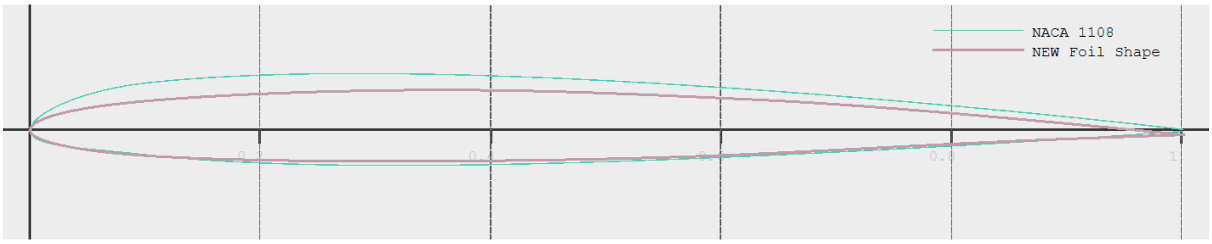


Figure 34: Airfoil shape comparison between NACA 1108 and a new airfoil design

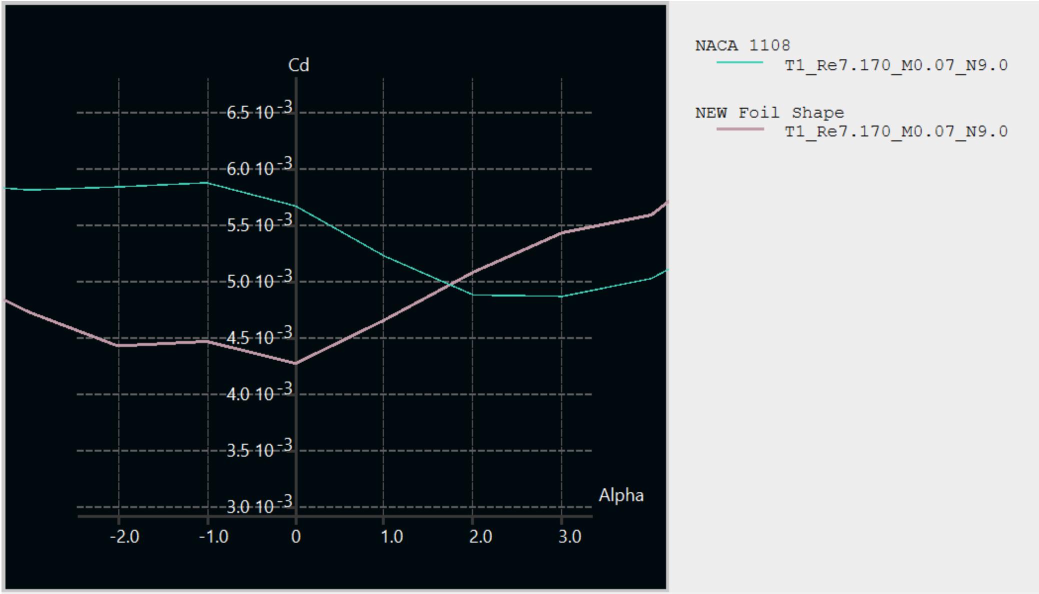


Figure 35: C_D vs α comparison between NACA 1108 and a new airfoil design

As seen in *Figure 36*, other airfoil characteristics such as C_L vs α are almost identical between both airfoils.

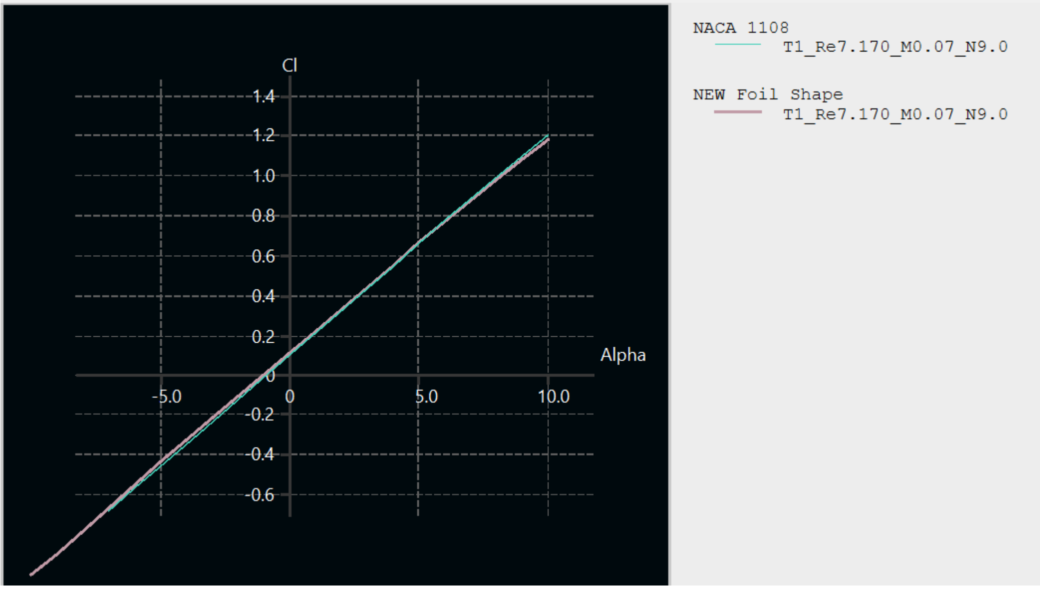


Figure 36: C_L vs α comparison between NACA 1108 and a new airfoil design

When this new airfoil shape design is inserted into Foil Design #3, the results are favourable. Due to the limitations of xflr5 in terms of asymmetric wings, two different wing configurations are analysed at the same time. The reasoning behind this is that at 50 knots, the intention is to have the foil wing as close to the water's surface as possible to increase windward force and reduce drag from the foil cant arm (see *4.2.2.* & *Figure 21*). Therefore, one of the wing configurations analysed has a dihedral of 0°, while the other has -30°. To obtain the real and total lift force, the results from both analyses will be halved and summed. Additionally, an ellipsoidal foil bulkhead was designed for this analysis. However, the bulkhead is not the objective of this analysis.

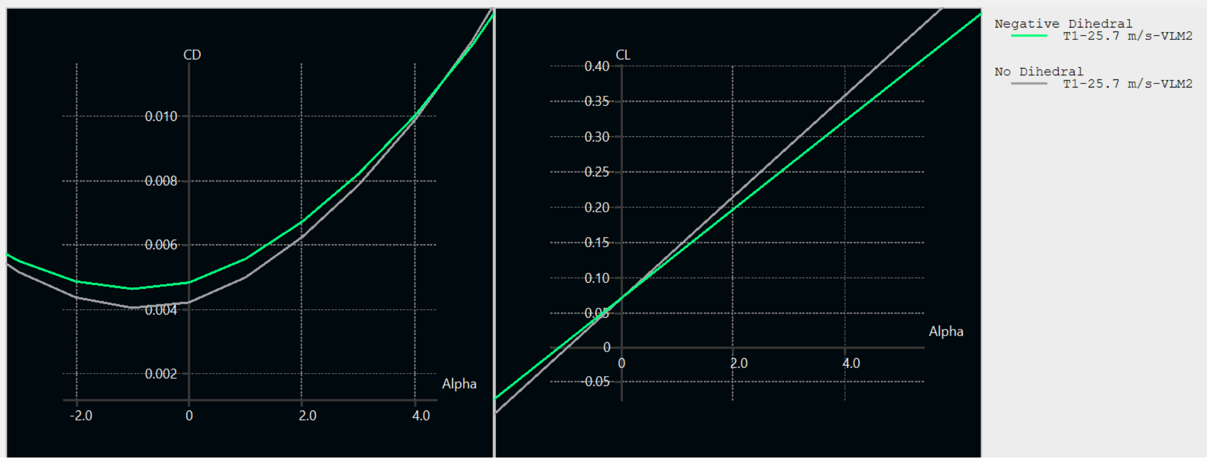


Figure 37: C_D vs α (left) & C_L vs α (right) comparison between 0º & -30º dihedral foil wings

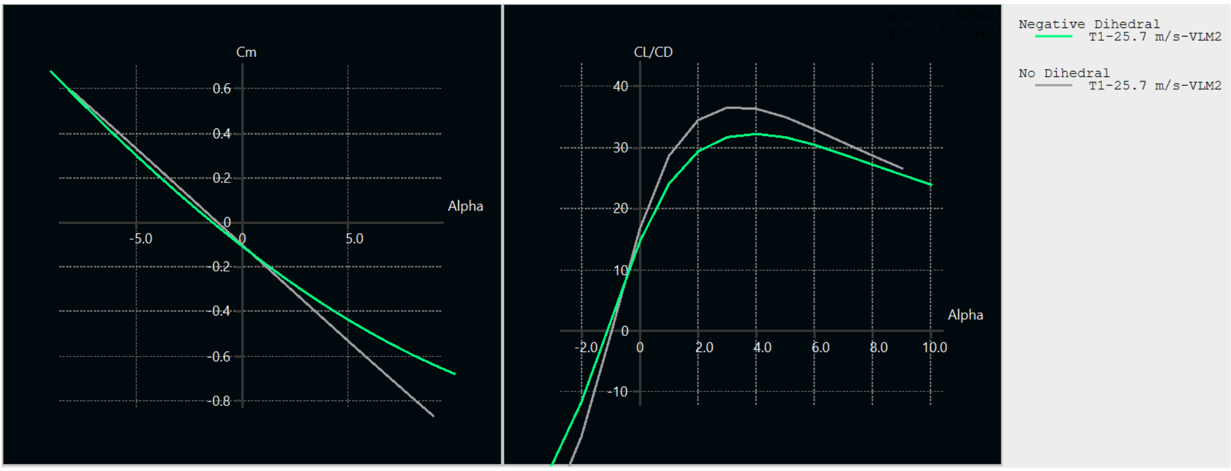


Figure 38: C_M vs α (left) & C_L/C_D vs α (right) comparison between 0º & -30º dihedral foil wings

To calculate the C_L necessary to produce a lift force equivalent to the yacht's weight, the following equation was devised:

$$C_{L\,req} = Weight\ /\ (0.5 * \varrho_{water} * A_{wing} * v^2)$$

The result of this equation showed that a C_L of 0.135 was required. At $\alpha = 1$º, a lift force of 70.86 kN is produced. Compared to the yacht plus crew weight of 69.44 kN, the generated lift is almost equivalent and slightly exceeds the value of weight, which is preferable considering that inconsistencies in the fluid (in the form of currents or waves, for example) and material rugosity are not considered in this analysis, and could reduce the lifting capacity of the foil wing. Additionally, the effect of the rudder's elevator will also reduce the generated lift force.

Looking at *Figure 38*, some important data can be extracted. Firstly, that the moment coefficient is equal to 0 at approximately α = -1°. The horizontal stabiliser section of the rudder will be essential to trim the yacht in this regard. Additionally, a maximum efficiency of 36.5 is achieved.

5.2.3. WINGLET ANALYSIS

To evaluate the drag reduction gained from the installation of winglets, a generic winglet design was created for the previous foil wing design.

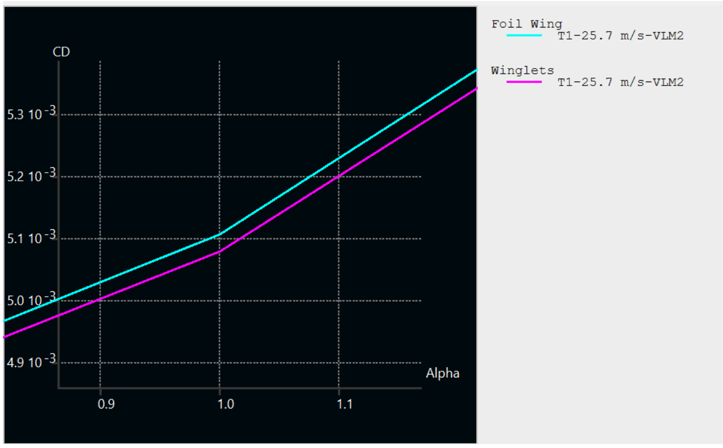


Figure 39: C_D vs α comparison between foil wing with and without winglets

While the analysis does show an improvement in drag coefficient of 0.39%, the difference is minimal. However, given that every gained centimetre in advantage is essential in the America's Cup, this feature will be included in the final design.

5.2.4. USE OF OPTIMIZATION SOFTWARE

To obtain a more precise optimization, the use of the Aeolus Aero wing optimization software was attempted. This software uses an algorithm to perform an optimization of a particular wing, given an objective, variables and constraints.

In this case, the subject of the optimization was a simple wing with the span, chord and dihedral limitations given by the Class Rule and the design intent. The objective of the optimization, similar to that of the manual optimization carried out using xflr5, was to minimise drag coefficient. Several iterations were performed in which the variables included span locations of each section, chord lengths, twist angles, sweep angles and dihedral angles of the last section so as to create an optimised winglet. As the main constraint, the lift force was limited to a range between 69kN and 70kN.

However, despite use of different program versions, devices, and optimization configurations, the result was at no point successful. *Figure 40* shows some of these unreasonable results. Having reached the point where all possible reasons that would explain the program's behaviour had been exhausted, the decision was made to stop this process and use the manual xflr5 optimization in the foil wing's final design.

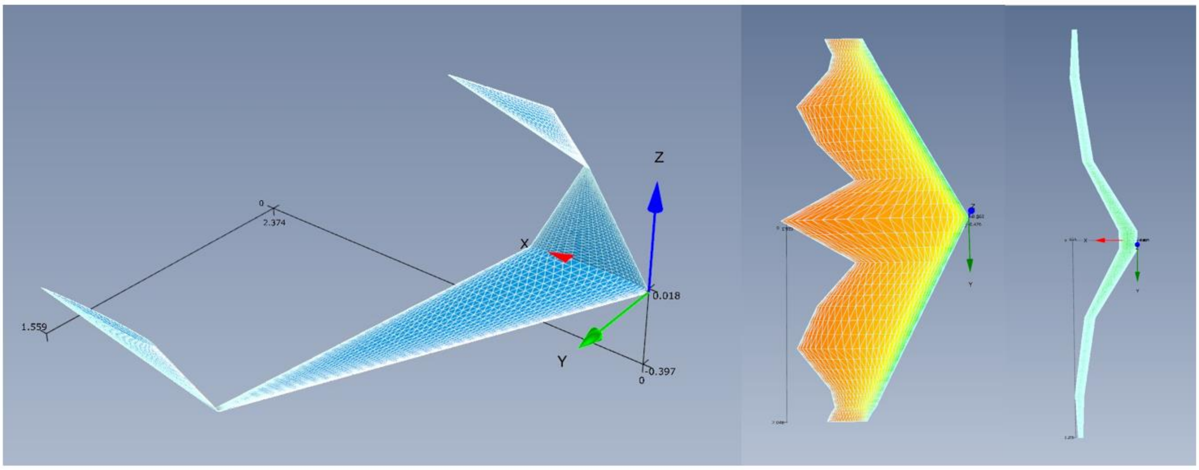


Figure 40: Aeolus Aero optimization failed results

5.3. RUDDER

5.3.1. YACHT TRIMMING

As mentioned earlier, the moment coefficient for the wing is currently 0 at -1° of angle of attack. In order to trim the yacht so that stability is achieved at an angle of attack of 1°, at which the desired lift force is achieved, an analysis must be performed to obtain the local angle of attack of the elevator. *Figure 42* shows the moment coefficient with respect to the angle of attack of the foil wing plus elevator set.

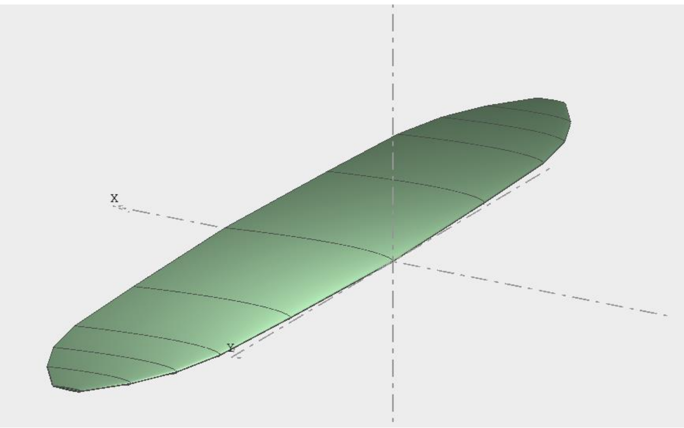


Figure 41: Xflr5 model of the elevator

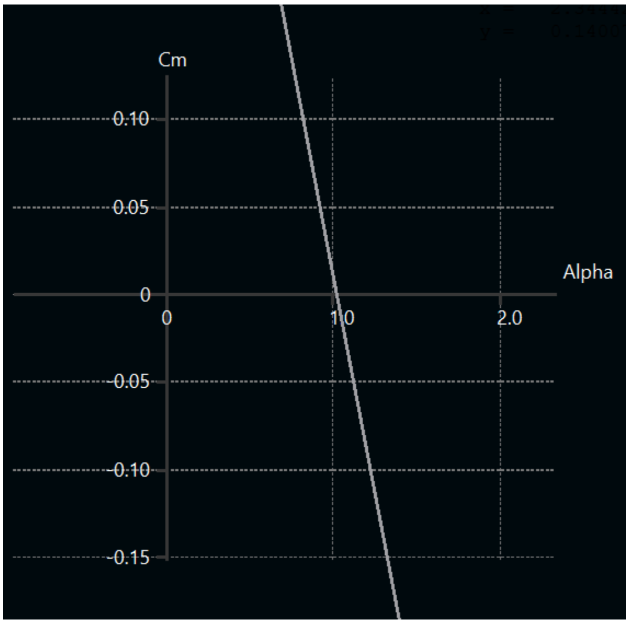


Figure 42: C_M vs α of the foil wing and elevator set

To achieve these results, the elevator's preliminary design was placed 10 m from the foil wing, i.e. at the TRP, with a local angle of attack of -1° and a NACA 0007 airfoil. The sharp slope of the C_M vs α line translates into an overly stable configuration, where any change in the yacht's angle of attack will be quickly corrected. Even if this configuration slightly sacrifices control, it will be essential to avoid touchdowns and crashes into the water.

Given that at 1º of yacht angle of attack, the local α of the elevator will be 0º, the negative lift generated will be null. Therefore the total lift force previously calculated will not be affected.

5.3.2. RUDDER AERODYNAMIC ANALYSIS

The complete preliminary design of the rudder was then modelled into OpenVSP and an aerodynamic analysis was performed to obtain the rudder's drag coefficient. The following figures contain the rudder's model, its C_D vs α graph and its aerodynamic efficiency.

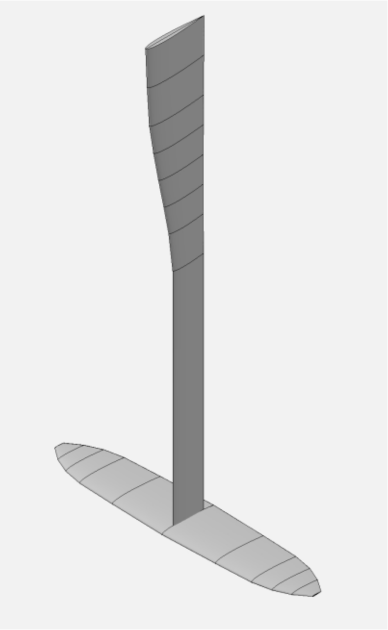


Figure 43: Rudder model analysed using OpenVSP

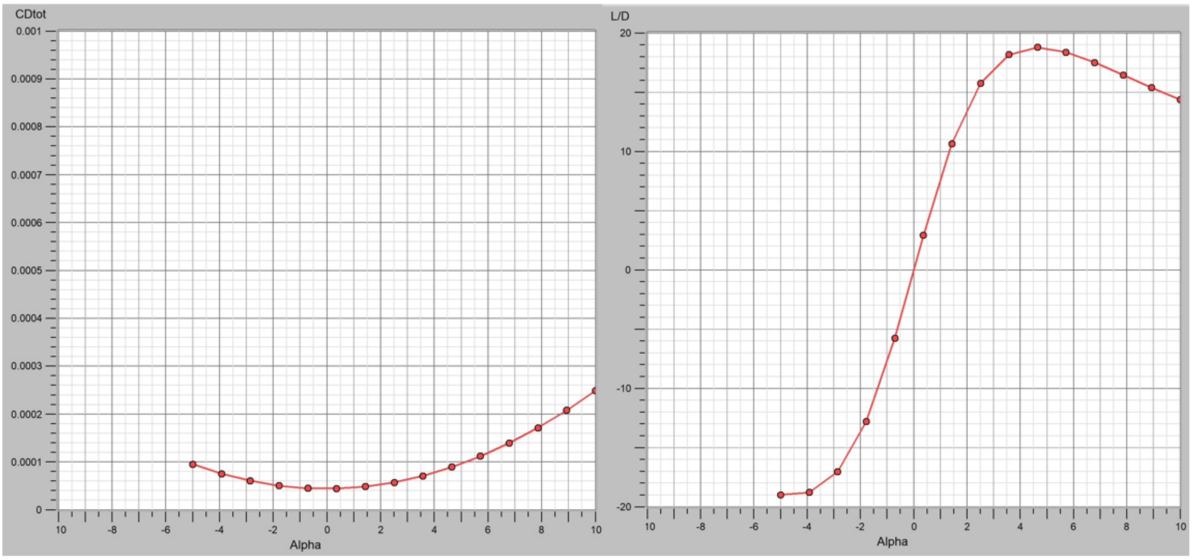


Figure 44: Aerodynamic properties of the rudder (C_D vs α left, L/D vs α right)

The results show that the drag properties of the rudder are excellent, which in turn provides great aerodynamic efficiency.

5.4. MAINSAIL

The objective of the mainsail's analysis will be to obtain its aerodynamic properties but most importantly, to calculate the increase in aerodynamic efficiency provided by the winglet in order to evaluate whether this design could offer an important advantage over the rest of the teams or not. *Figure 45* shows the aerodynamic analysis of the mainsail without the winglet and *Figure 46* does the same for the mainsail with winglet.

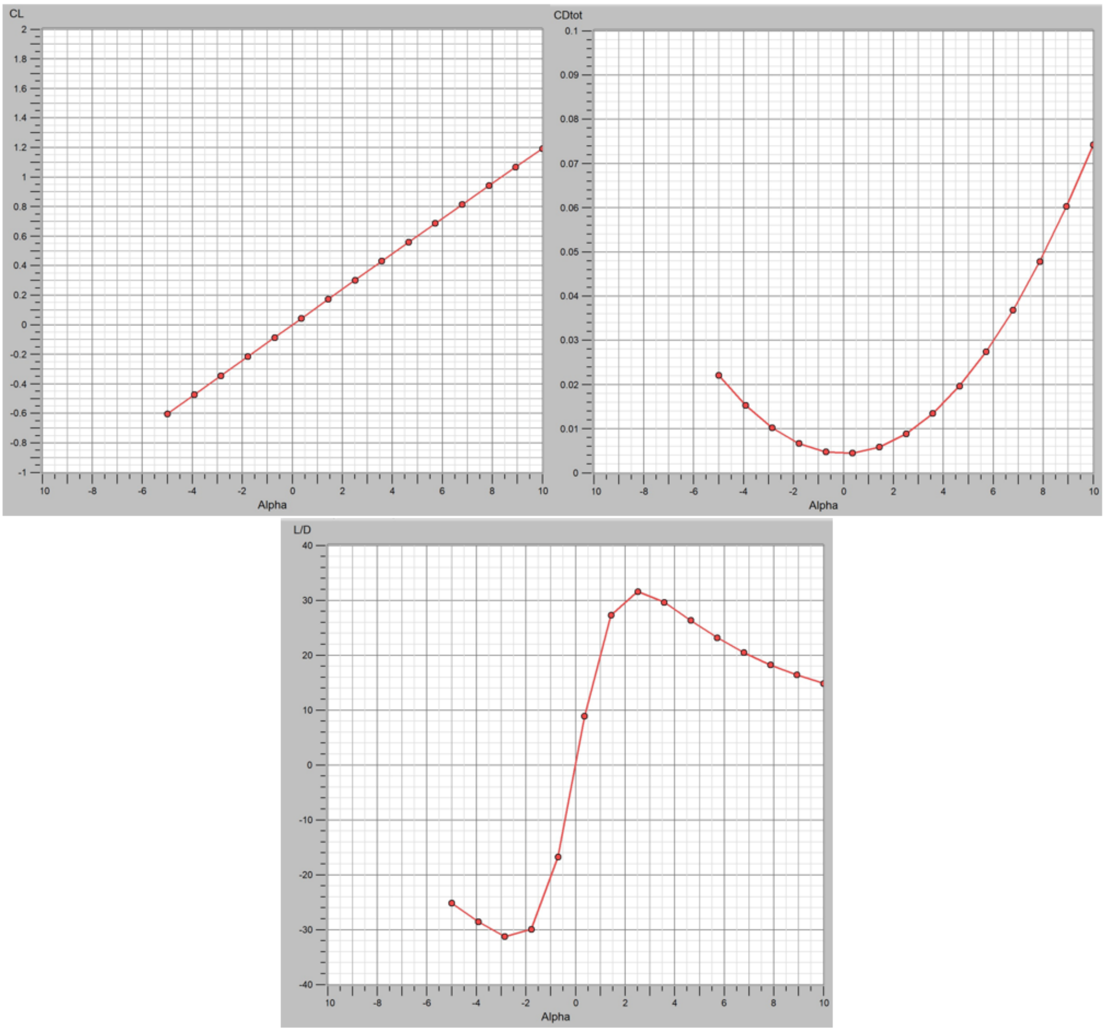


Figure 45: Aerodynamic analysis of mainsail without winglet (C_L vs α top left, $C_D$vs α top right, L/Dvs α bottom)

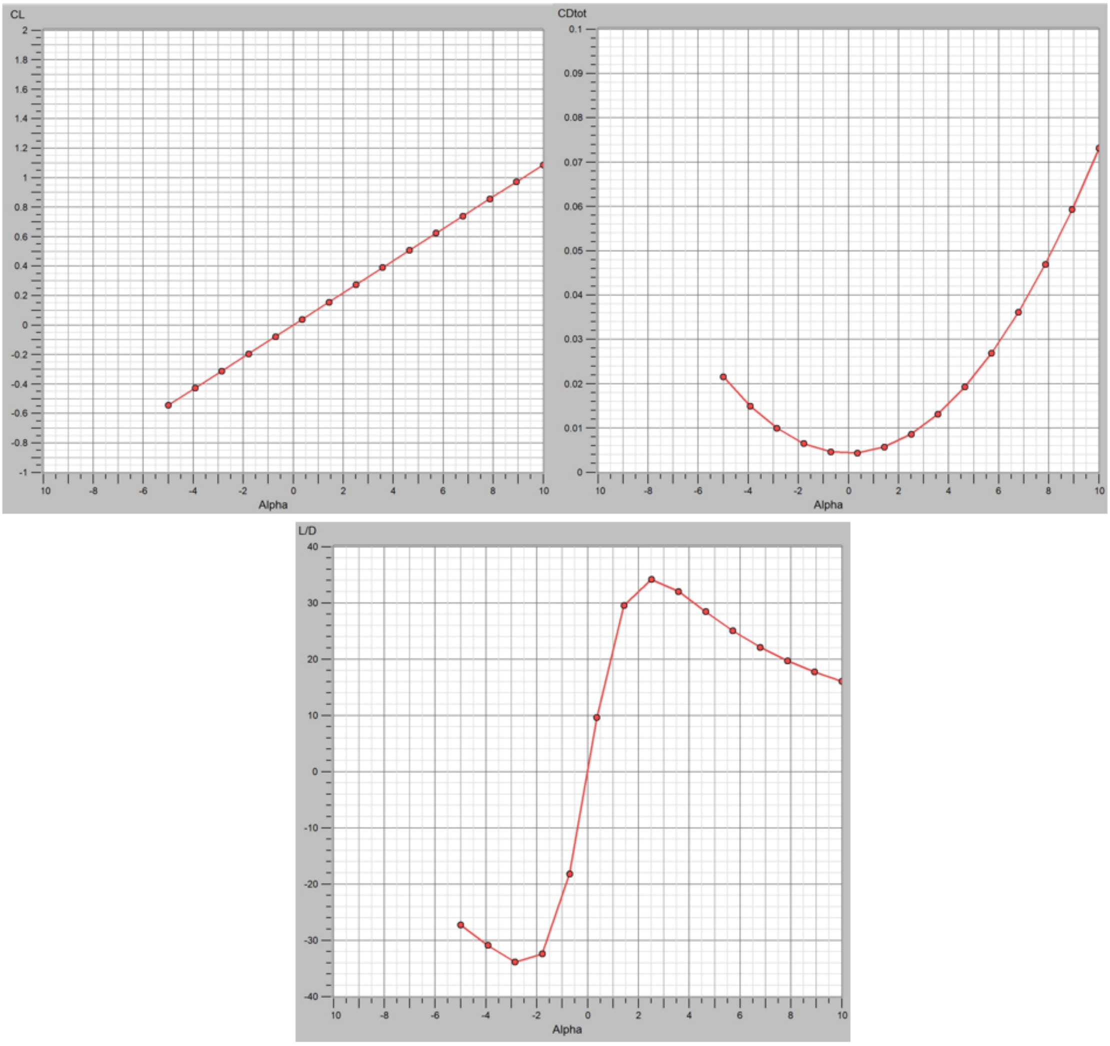


Figure 46: Aerodynamic analysis of mainsail with winglet (C_L vs α top left, C_D vs α top right, L/D vs α bottom)

The results show an increase in aerodynamic efficiency of 5.88%. This would be a groundbreaking upgrade that could potentially offer a large advantage over the rest of the competitors. These results lock the mainsail winglet as one of the characteristics of the Final Mainsail Design. The following figure contains both of the models employed in this analysis.

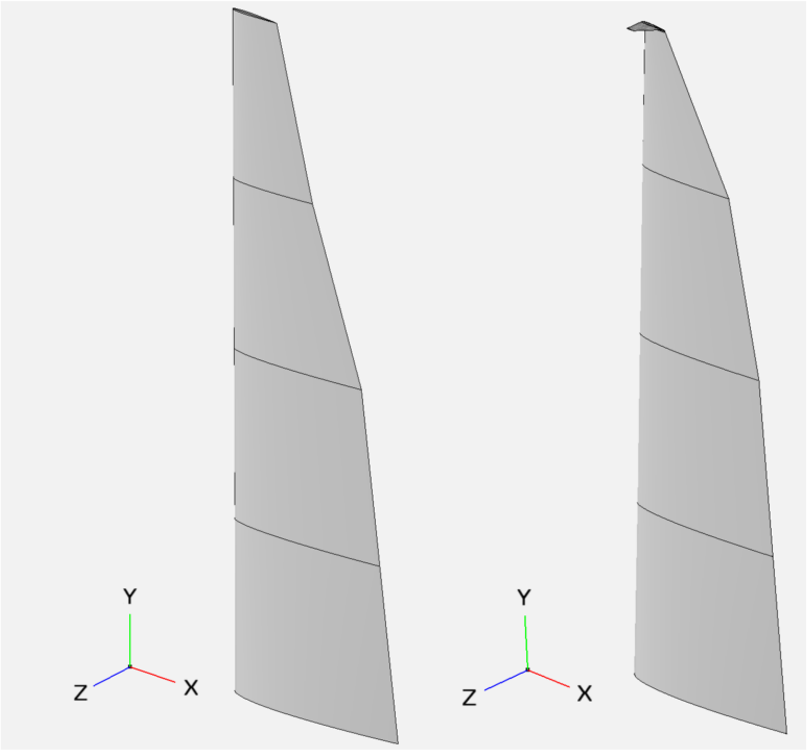


Figure 47: Mainsail models analysed using OpenVSP (no winglet left, winglet right)

CHAPTER 6. FINAL DESIGN

6.1. HULL

6.1.1. MODEL & MAIN FEATURES

After a successful analysis, the hull model was imported into Catia for creation of the final assembly model. *Figure 48* shows an isometric view of the model, while *Figure 49* contains the three main views.

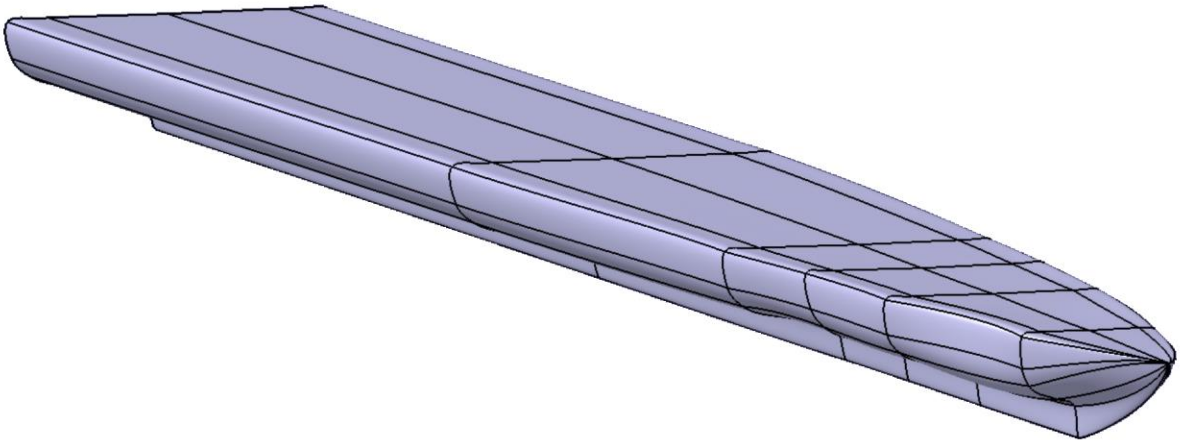


Figure 48: Isometric view of the Final Hull Design

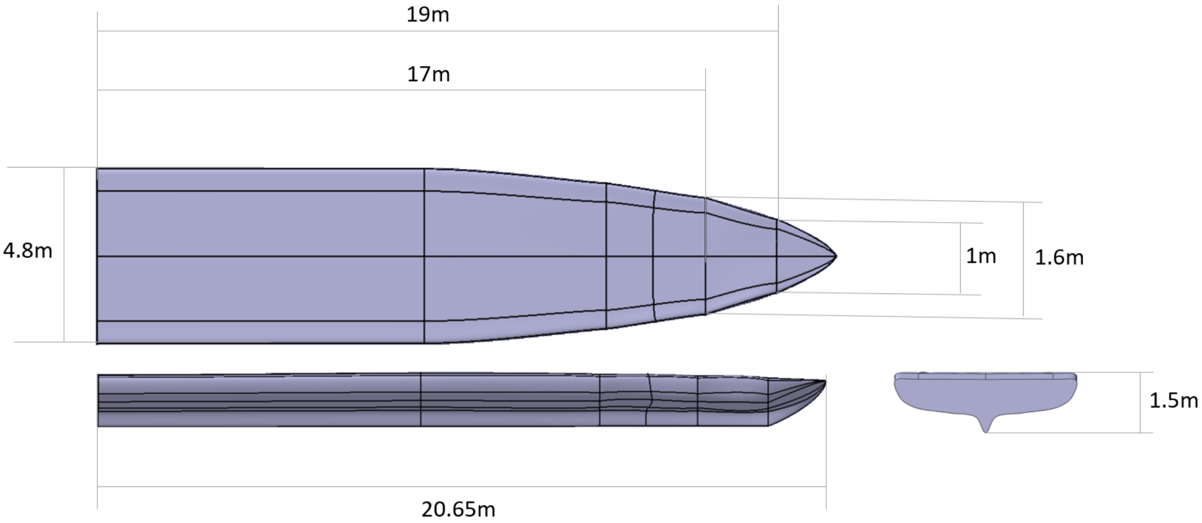


Figure 49: Three main views of the Final Hull Design

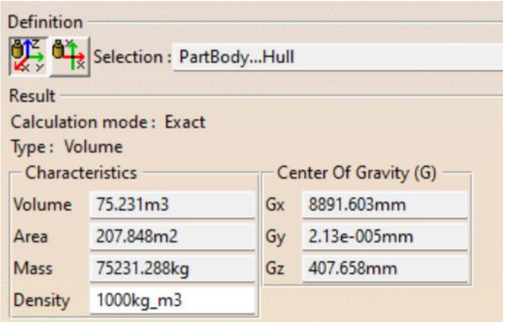
The main feature of the Final Hull Design is a bustle that extends longitudinally throughout the entire hull. It will help reduce induced drag, minimise the amount of wetted surface in case of touchdown between the hull and the water's surface, and help with separating the hull from the water's surface on acceleration. Additionally, the perimeter line is slightly lowered, achieving a gain in material properties due to Class Rule limitations as well as a possible manoeuvre time reduction.

6.1.2. MANUFACTURING PROPOSAL

The manufacturing process of the hull will involve the fabrication of two separate sandwich structures, one for the deck using para-aramid honeycomb, and the other for the hull lower surface. These parts will be cured separately and finally joined with a strong adhesive at the perimeter line. For the placement of the fibres, the use of AFP tooling is recommended. Additionally, draining holes would have to be machined after the fabrication of each part, and fairing flaps could be installed.

6.1.3. CLASS RULE COMPLIANCE

As seen in the previous *Figure 49*, the hull dimensions coincide with those established by the Class Rule. Additionally, no para-aramid honeycomb is placed under the perimeter line, given that the perimeter line itself has been lowered. Finally, the CATIA model is calculated to contain a volume of 75.23 m^3, which is above the minimum volume of 60 m^3 established by the Class Rule. This measurement is shown in *Figure 50*, but note that the density shown is one given by the default.


Definition
Selection : PartBody...Hull
Result
Calculation mode : Exact
Type : Volume

Characteristics		Center Of Gravity (G)	
Volume	75.231m3	Gx	8891.603mm
Area	207.848m2	Gy	2.13e-005mm
Mass	75231.288kg	Gz	407.658mm
Density	1000kg_m3		

Figure 50: Volume measurement of the Final Hull Design using CATIA

Finally, one of the important considerations in terms of hull cross section shape involved the containment of the foil cant axis. As shown in the following CATIA model, the foil cant axis is fully contained.

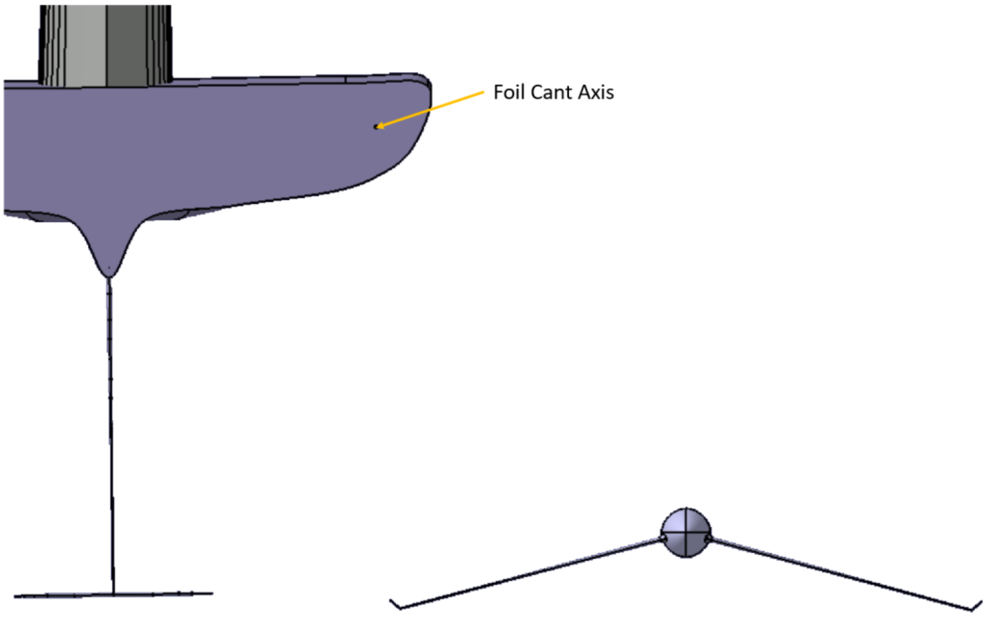


Figure 51: Foil cant axis containment in hull surface

6.2. FOILS

6.2.1. MODEL & MAIN FEATURES

Having analysed and manually optimised the foil's preliminary design, a final design can be defined. The xflr5 model was exported into Catia, where machining radii can be more easily modelled. *Figure 52* shows an isometric view of the model, while *Figure 53* contains the three main views.

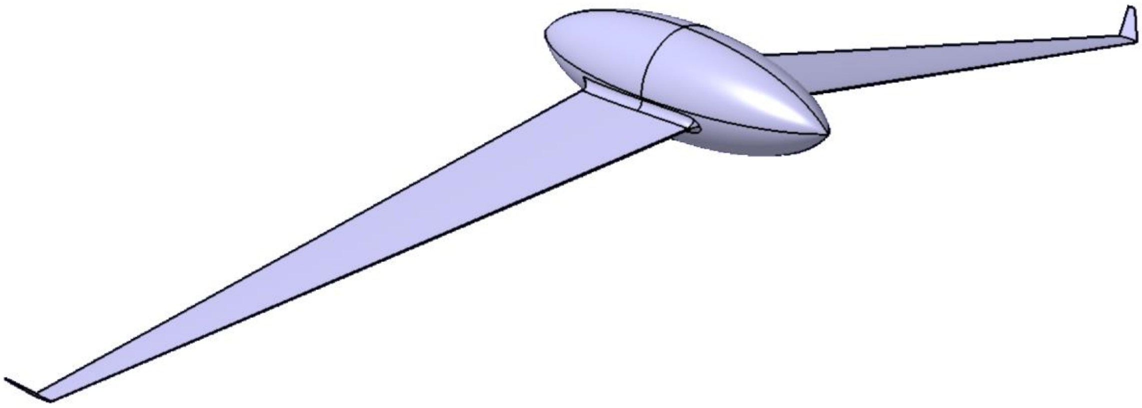


Figure 52: Isometric view of the Final Foil Design

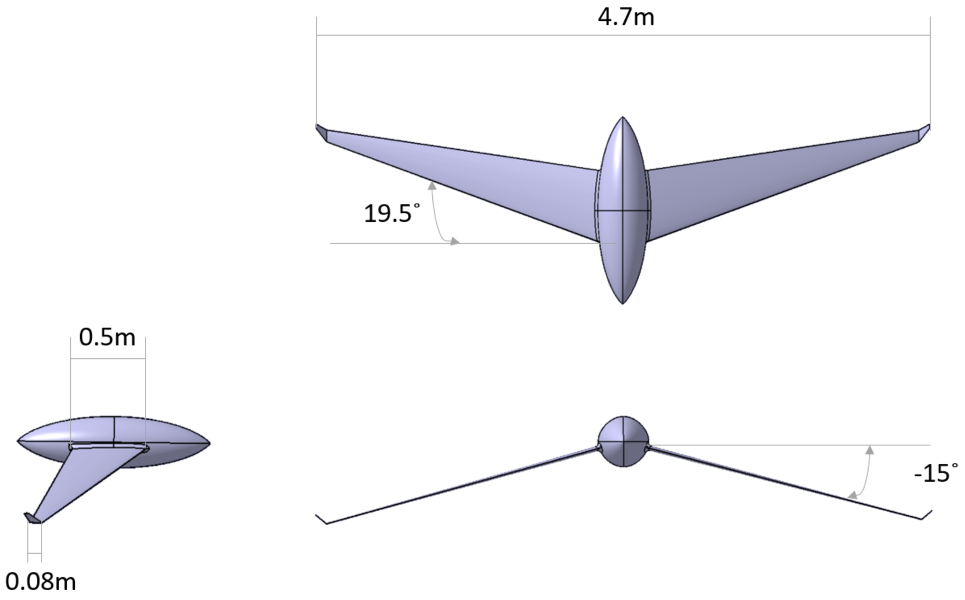


Figure 53: Three main views of the Final Foil Design

The main features of the Final Foil Design include:

- Negative dihedral: The foil wing has a negative dihedral angle of -15º. This will reduce the amount of foil arm cross section inside the water when sailing at speeds of 50 knots and will therefore decrease drag.

- Winglets: The foil wing has winglets at both tips, which ensures a reduction in induced drag

- Low thickness, low camber profile: The foil wing has a low thickness and low camber profile with the objective of further reducing parasitic drag. This decision comes hand-in-hand with a reduction in lift force, but it has been ensured that at 50 knots and with no flap deflection, the lift force is slightly higher than the yacht and crew's total weight.

- Generic bulkhead: A generic bulkhead was designed for this final foil design. The aerodynamic optimization of the bulkhead's shape and its size are out of the scope of this project.

6.2.2. MANUFACTURING PROPOSAL

The manufacturing process of this part was taken into account during its design. One of the main differences in this respect to competitors is the machining of the winglet together with the rest of the foil wing. Other teams, such as Luna Rossa, made the decision of fabricating the winglet separately. A possible reason for this decision is that winglet analysis may take longer and time constraints force these parts to be manufactured separately. While a single-element design will require more complex tools and machines, it will get rid of interfaces which could increase drag.

On the other hand, flaps must be fabricated separately from the rest of the foil wing, and it's possible that hinge size requirements could force a redesign of the wing profile to increase its thickness. The interface between the flaps and the wing will be covered with an elastic membrane to make the aerodynamic surface as smooth as possible.

6.2.3. CLASS RULE COMPLIANCE

As seen in *Figure 54*, the Final Foil Design fits perfectly within the Foil Wing Box detailed in the AC75 Class Rule.

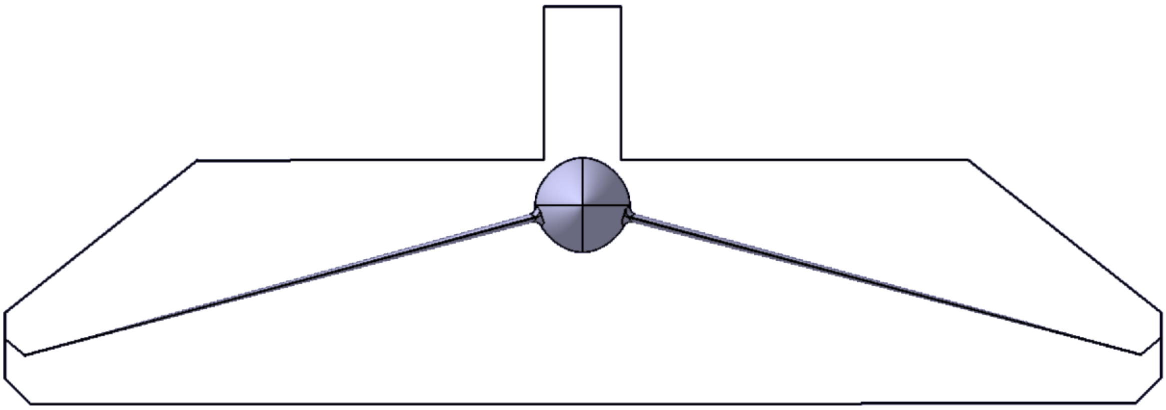


Figure 54: Final Foil Design within Foil Wing Box restrictions

Additionally, the aftmost point of the foil's bulkhead is adjacent to the limiting plane located 10m forward of the TRP, as explained in the foil's preliminary design. Finally, the foil wing is perfectly symmetrical about the wing symmetry plane and two foil flap segments are considered, which extend from the trailing edge to 50% of the wing's chord. This confirms that the design is in compliance with the Class Rule.

6.3. RUDDER

6.3.1. MODEL & MAIN FEATURES

Having ensured the trimming of the yacht through the rudder analysis, the final model can be defined in CATIA. The following figures show an isometric view of the model as well as the three main views.

Figure 55: Isometric view of the Final Rudder Design

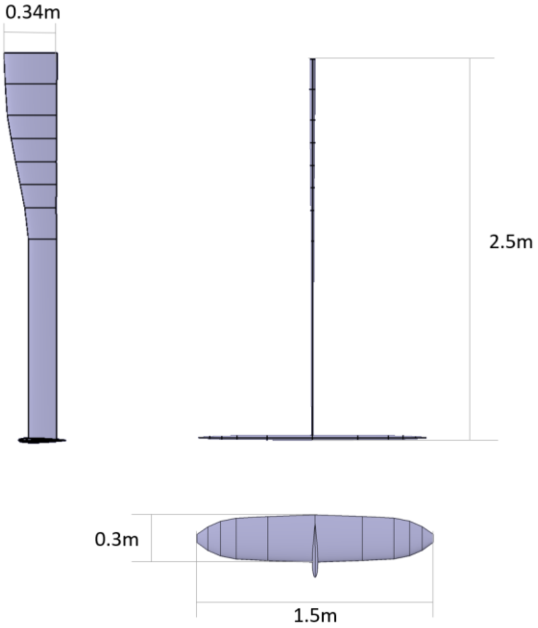


Figure 56: Three main views of the Final Rudder Design

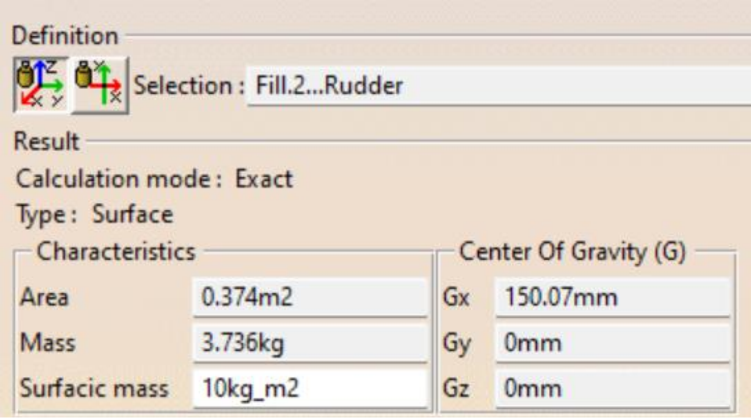
The main features of the rudder include an elliptical elevator, which provides excellent aerodynamic efficiency; a long rudder, since it must be able to function at all yacht foiling heights; and very thin aerodynamic profiles, in order to minimise drag.

6.3.2. MANUFACTURING PROPOSAL

Since no weight limitations are given for the rudder, its fabrication would be one of the final decisions in the design loop of the yacht, since its position at the TRP could largely affect the overall yacht LCG depending on the use of metal or composite materials. For the control surfaces, a similar approach to that of the foil flaps would be taken, covering their interface with elastic membranes in order to smooth the aerodynamic surface.

6.3.3. CLASS RULE COMPLIANCE

The rudder is located within the dimensional limits established by the Class Rule. The rudder's trailing edge is in contact with the TRP and it extends neither longitudinally nor transversely from planes set 1.5m forward of the TRP or at either side of the LCP. Moreover, in compliance with the Rule, the last 0.5m of the rudder has an area larger than 0.3m^2 when projected onto the MWP as seen in *Figure 57*. Finally, the rudder is uniquely in contact with the hull lower surface.



Definition

Selection : Fill.2...Rudder

Result

Calculation mode : Exact

Type : Surface

Characteristics		Center Of Gravity (G)	
Area	0.374m2	Gx	150.07mm
Mass	3.736kg	Gy	0mm
Surfacic mass	10kg_m2	Gz	0mm

Figure 57: Area of the final 0.5m of the rudder projected onto the MWP

6.4. MAINSAIL

6.4.1. MODEL & MAIN FEATURES

Having proven the viability and effectiveness of the winglet on the mainsail, the Final Mainsail Design can be exported into CATIA. The next figures show an isometric view of the model as well as the three main views.

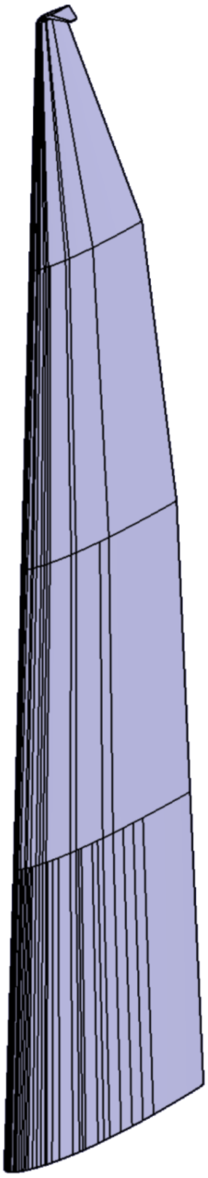


Figure 58: Isometric view of the Final Mainsail Design

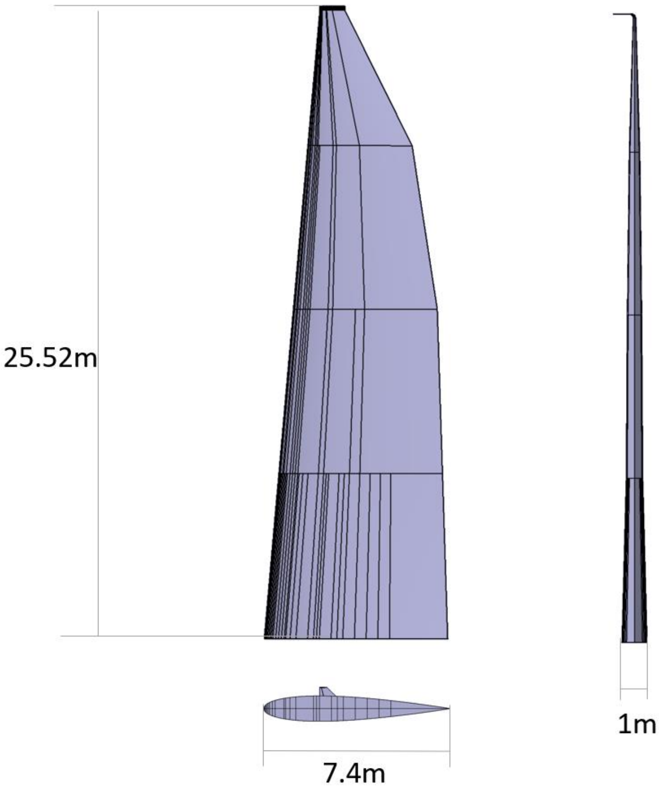


Figure 59: Three main views of the Final Mainsail Design

The main features of the Final Mainsail Design include the innovative use of a winglet at the mainsail's tip, which increases aerodynamic efficiency by more than 5%; the use of a thick symmetric airfoil, particularly the NACA 0014, in order to fit all of the mainsail systems between the sail skins; a boomless configuration in which the rigging is located under the deck, closing the gap between the mainsail's base and the hull; and a mainsail girth distribution which favours the descent of the centre of pressures.

6.4.2. CLASS RULE COMPLIANCE

As explained during the study of the Class Rule and the preliminary design of the mainsail, the interpretability of the mainsail's rules has led to the creation of a wing tip element that could possibly bring an advantage over the other teams. Two possible designs, one using the fairing between sail skins and the other using the sail skins themselves, were devised (see *4.4.2. Winglet Design Options*).

The limitations in terms of mainsail girths were complied with, closing the upper limit on the girths closer to the base, and the lower limit on the girths closer to the mainsail's head. Finally, there is a girth formula in the Class Rule which is algo complied with:

$$130.0 < \frac{26.5}{12} \times (G_F + 4G_{25} + 2G_{50} + 4G_{75} + G_H) < 145.0$$

$$130.0 < \frac{26.5}{12} \times (7.4 + 4*6.6 + 2*5.8 + 4*4.2 + 2.5) < 145.0$$

$$130.0 < 142.879 < 145.0$$

6.5. FINAL PRODUCT

The resulting product is made up of the main elements which make up the AC75: hull, foils, rudder and mainsail. The following figure shows the final result as modelled in CATIA for this project's AC75, baptised with the name "Sea Bravo".

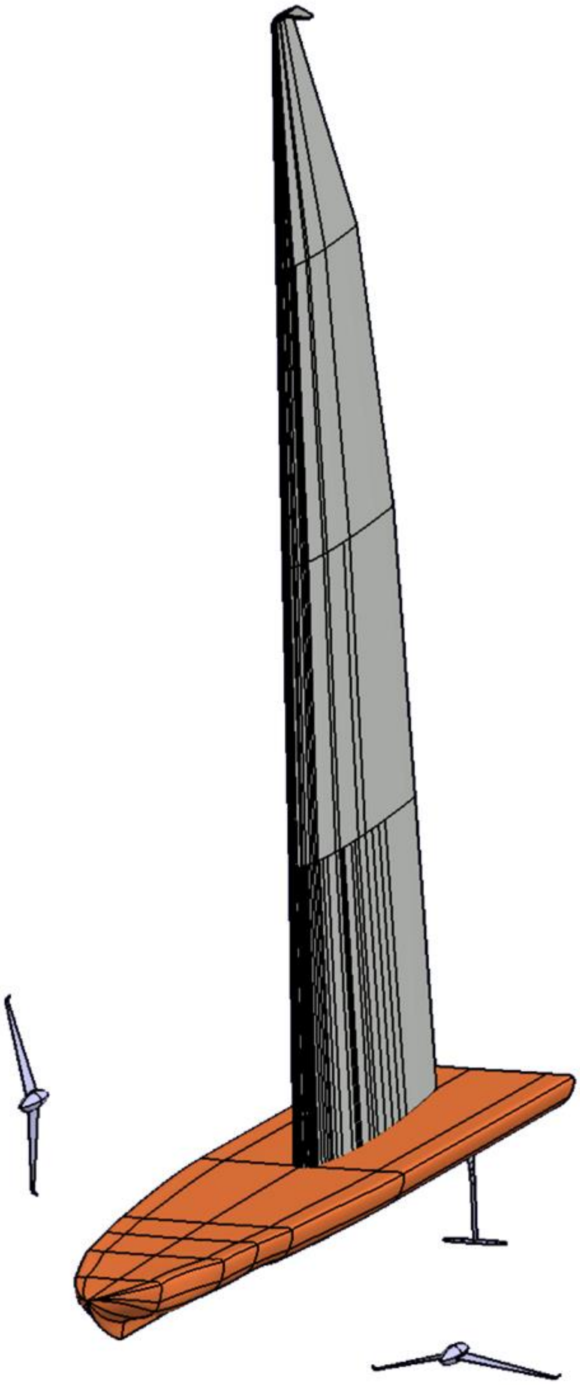


Figure 60: Final model of the Sea Bravo AC75

7. CONCLUSION

The design of the Sea Bravo AC75 was achieved through an intense study of the AC75 Class Rule, the observation of the four teams of the 36th America's Cup, the creation of several preliminary designs, and the modelling and analysis of said designs.

The main design driver throughout the entire yacht is the reduction of drag coefficient. The analysis of each of the four main elements demonstrated the effectiveness of the design in this regard where, contrary to aircraft design, the lift force generated had to be limited. Other aspects, such as the trimming of the foils with the elevator and the search for increased efficiency in the dimensionally limited mainsail, were more alike to how an aircraft's initial design is performed. In hindsight, several decisions were made throughout the project which involved the sacrifice of yacht control and manoeuvrability. The true effect of these kinds of trade-offs can be studied with the creation of testing boats, which are essential in the analysis of more extreme ideas, as is the case of Alinghi Red Bull Racing's tubercle foil.

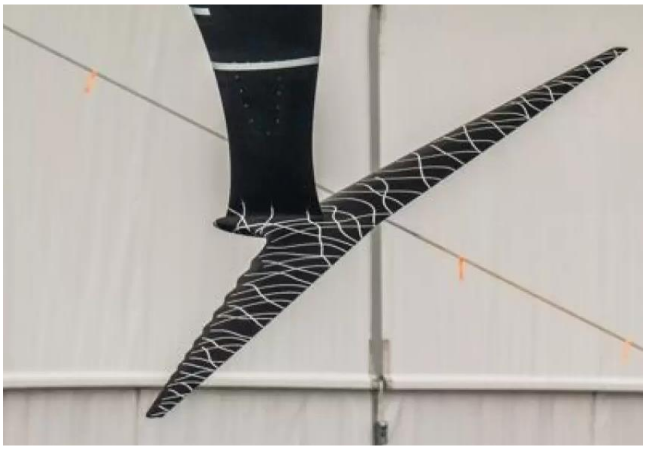
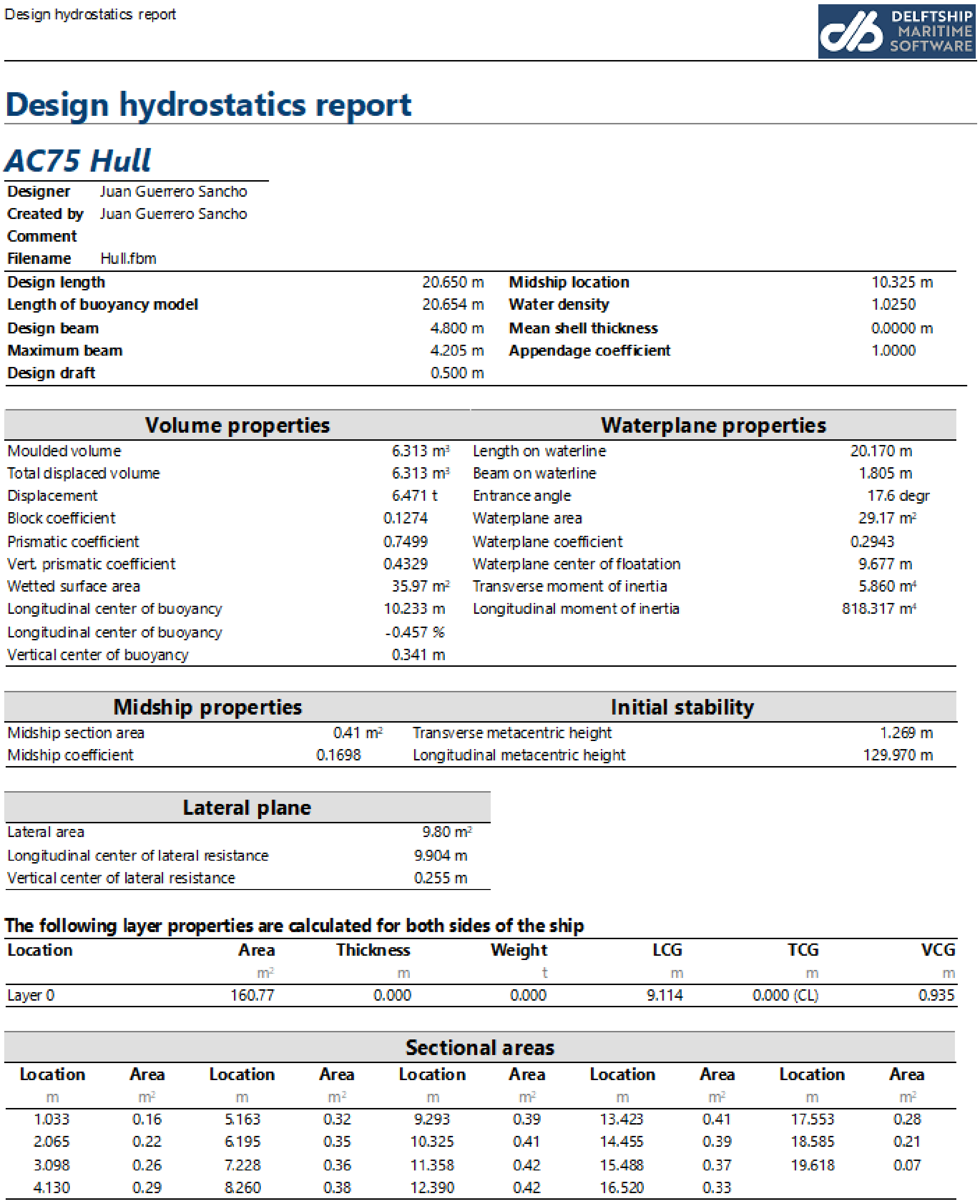


Figure 61: Alinghi Red Bull Racing's new tubercle foil [AC, 2023]

One of the most important turning points in the project came at the realisation that the design scope had to evolve from focusing on generating the largest possible lift force with the foils to minimising drag generation, even at the expense of lift. Another important peak of the project's evolution lies in the brainstorming of the mainsail winglet's design, which involved going back and forth to the Class Rule in order to evaluate the validity of the different ideas.

ANNEX I: FULL HYDROSTATICS REPORT



Design hydrostatics report

Design hydrostatics report

AC75 Hull

Designer	Juan Guerrero Sancho
Created by	Juan Guerrero Sancho
Comment	
Filename	Hull.fbm

Design length	20.650 m	**Midship location**	10.325 m
Length of buoyancy model	20.654 m	**Water density**	1.0250
Design beam	4.800 m	**Mean shell thickness**	0.0000 m
Maximum beam	4.205 m	**Appendage coefficient**	1.0000
Design draft	0.500 m		

Volume properties		**Waterplane properties**	
Moulded volume	6.313 m³	Length on waterline	20.170 m
Total displaced volume	6.313 m³	Beam on waterline	1.805 m
Displacement	6.471 t	Entrance angle	17.6 degr
Block coefficient	0.1274	Waterplane area	29.17 m²
Prismatic coefficient	0.7499	Waterplane coefficient	0.2943
Vert. prismatic coefficient	0.4329	Waterplane center of floatation	9.677 m
Wetted surface area	35.97 m²	Transverse moment of inertia	5.860 m⁴
Longitudinal center of buoyancy	10.233 m	Longitudinal moment of inertia	818.317 m⁴
Longitudinal center of buoyancy	-0.457 %		
Vertical center of buoyancy	0.341 m		

Midship properties		**Initial stability**	
Midship section area	0.41 m²	Transverse metacentric height	1.269 m
Midship coefficient	0.1698	Longitudinal metacentric height	129.970 m

Lateral plane	
Lateral area	9.80 m²
Longitudinal center of lateral resistance	9.904 m
Vertical center of lateral resistance	0.255 m

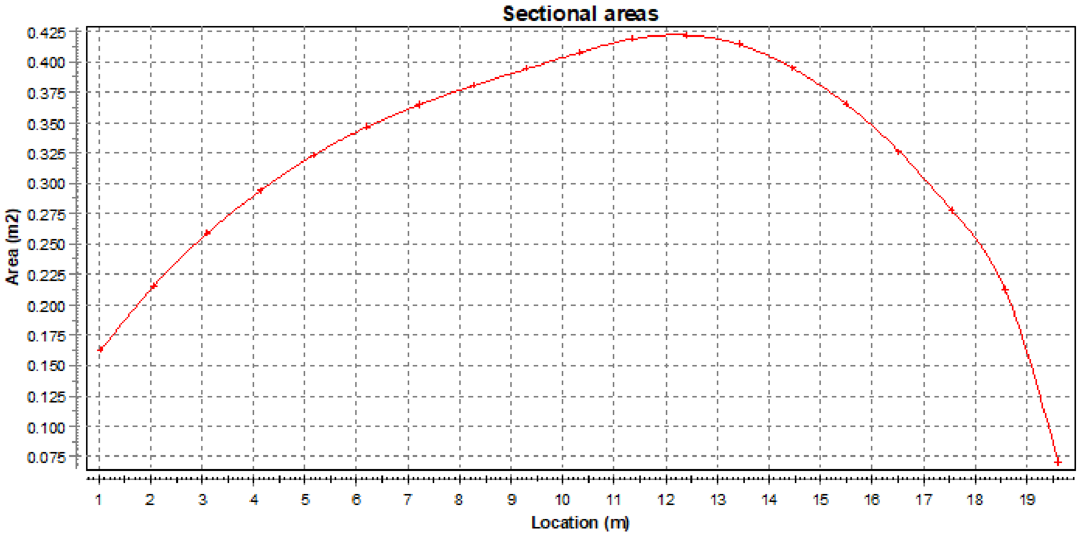
The following layer properties are calculated for both sides of the ship

Location	Area m²	Thickness m	Weight t	LCG m	TCG m	VCG m
Layer 0	160.77	0.000	0.000	9.114	0.000 (CL)	0.935

Sectional areas

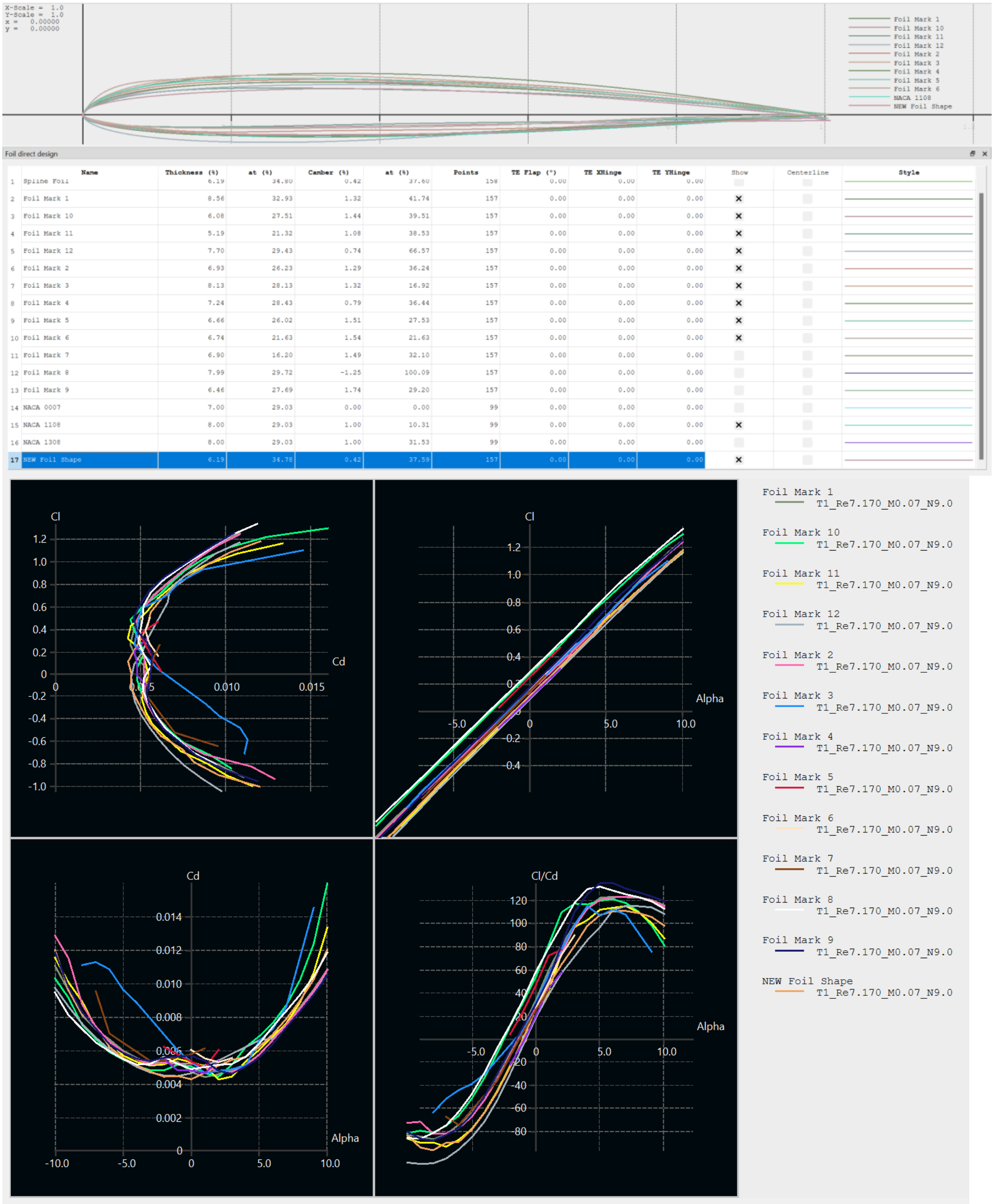
Location m	Area m²	Location m	Area m²	Location m	Area m²	Location m	Area m²	Location m	Area m²
1.033	0.16	5.163	0.32	9.293	0.39	13.423	0.41	17.553	0.28
2.065	0.22	6.195	0.35	10.325	0.41	14.455	0.39	18.585	0.21
3.098	0.26	7.228	0.36	11.358	0.42	15.488	0.37	19.618	0.07
4.130	0.29	8.260	0.38	12.390	0.42	16.520	0.33		

Design hydrostatics report



NOTE 1: Draft (and all other vertical heights) is measured from base Z=0.000
NOTE 2: All calculated coefficients based on project length, draft and beam.

ANNEX II: AIRFOIL SHAPE MANUAL OPTIMIZATION ITERATIONS



	Name	Thickness (%)	at (%)	Camber (%)	at (%)	Points	TE Flap (°)	TE XHinge	TE YHinge	Show	Centerline	Style
1	Spline Foil	6.19	34.80	0.42	37.60	158	0.00	0.00	0.00	☐	☐	—
2	Foil Mark 1	8.56	32.93	1.32	41.74	157	0.00	0.00	0.00	☒	☐	—
3	Foil Mark 10	6.08	27.51	1.44	39.51	157	0.00	0.00	0.00	☒	☐	—
4	Foil Mark 11	5.19	21.32	1.08	38.53	157	0.00	0.00	0.00	☒	☐	—
5	Foil Mark 12	7.70	29.43	0.74	66.57	157	0.00	0.00	0.00	☒	☐	—
6	Foil Mark 2	6.93	26.23	1.29	36.24	157	0.00	0.00	0.00	☒	☐	—
7	Foil Mark 3	8.13	28.13	1.32	16.92	157	0.00	0.00	0.00	☒	☐	—
8	Foil Mark 4	7.24	28.43	0.79	36.44	157	0.00	0.00	0.00	☒	☐	—
9	Foil Mark 5	6.66	26.02	1.51	27.53	157	0.00	0.00	0.00	☒	☐	—
10	Foil Mark 6	6.74	21.63	1.54	21.63	157	0.00	0.00	0.00	☒	☐	—
11	Foil Mark 7	6.90	16.20	1.49	32.10	157	0.00	0.00	0.00	☐	☐	—
12	Foil Mark 8	7.99	29.72	-1.25	100.09	157	0.00	0.00	0.00	☐	☐	—
13	Foil Mark 9	6.46	27.69	1.74	29.20	157	0.00	0.00	0.00	☐	☐	—
14	NACA 0007	7.00	29.03	0.00	0.00	99	0.00	0.00	0.00	☐	☐	—
15	NACA 1108	8.00	29.03	1.00	10.31	99	0.00	0.00	0.00	☒	☐	—
16	NACA 1308	8.00	29.03	1.00	31.53	99	0.00	0.00	0.00	☐	☐	—
17	NEW Foil Shape	6.19	34.78	0.42	37.59	157	0.00	0.00	0.00	☒	☐	—

BIBLIOGRAPHY

America's Cup. (2022, March 17). AC75 Class Rule v2.0 [PDF]. America's Cup. https://www.americascup.com/files/m5498_AC75-Class-Rule-v20.pdf

America's Cup. (n.d.). 37th America's Cup. Retrieved December 18, 2022, from https://www.americascup.com/

Sailing World. (2022, November 30). Sailing World. Retrieved December 18, 2022, from https://www.sailingworld.com/americas-cup/

Sail World. (2022). Sail World - the world's largest Sailing News Network. Retrieved December 18, 2022, from https://www.sail-world.com/Europe

Mozzy Sails. (n.d.). Mozzy Sails Youtube Channel [Video file]. Retrieved December 18, 2022, from https://www.youtube.com/c/mozzysails

C. A. Marchaj. (1979) Aero-Hydrodynamics of Sailing. New York, USA: Dodd, Mead & Company.

R. Gladwell (2019, September 15) America's Cup: Images and video reveal American Magic's novel design approach. Retrieved March 20, 2023 from https://www.sail-world.com/news/222034/Americas-Cup-AC75-American-Magic-revealed

M. Chisnell (2021, January 8) The Flying Technology of the AC75. Retrieved March 20, 2023 from https://www.sailingworld.com/story/racing/flying-technology-of-the-ac75/

C-Tech (2021, March 11) The Tech Inside AC75 Soft Wings. Retrieved March 20, 2023 from https://www.c-tech.co.nz/news/the-tech-inside-ac75-soft-wings

Scuttlebutt Sailing News (2021, February 2) America’s Cup: Designing the best AC75. Retrieved March 20, 2023 from https://www.sailingscuttlebutt.com/2021/02/02/americas-cup-designing-the-best-ac75/

G. E. Kremer (2012, July) Application of axiomatic design, TRIZ, and mixed integer programming to develop innovative designs: A locomotive ballast arrangement case study. Retrieved March 20, 2023 from https://www.researchgate.net/figure/List-of-materials-with-their-density-and-cost_tbl3_257336434

C. Trento (n.d.) How Are Tungsten Alloys Used in the Aerospace Industry? Retrieved March 20, 2023 from https://www.samaterials.com/content/how-are-tungsten-alloys-used-in-the-aerospace-industry.html

Composites One (n.d.) Core Materials. Retrieved March 20, 2023 from https://www.compositesone.com/product/core-materials/

Plascore (n.d.) Aramid (Meta-Aramid/Para-Aramid) Honeycomb Cores. Retrieved March 20, 2023 from https://www.plascore.com/honeycomb/honeycomb-cores/aramid-fiber/

America's Cup (2021) America's Cup Youtube Channel [Video file] Retrieved March 20, 2023 from https://www.youtube.com/@americascup

Scuttlebutt Sailing News (2021, May 6) Luna Rossa: it's about the foils. Retrieved March 20, 2023 from https://www.sailingscuttlebutt.com/2021/05/06/luna-rossa-its-about-the-foils/

M. Hepperle. (2018, May 21). Special considerations for Hydrofoils. Retrieved April 22, 2023, from https://www.mh-aerotools.de/airfoils/hydrofoils.htm

T. Morris. (2021, January 26). America's Cup Foil Problem and the ETNZ Rule Loophole [Video file]. Retrieved April 30, 2023, from https://www.youtube.com/watch?v=dccTjmkG9to

F. Chevalier, J. Taglang. (2019, December 18). The new flying mono hulls of the America's Cup. Retrieved May 9, 2023, from http://chevaliertaglang.blogspot.com/2019/12/ac75-2021-americas-cup-1st-generation.html

W. Sunnucks. (2021, February 16). America's Cup AC75 - Insights from a Vampire. Retrieved May 20, 2023, from https://vampire-project.com/2021/02/16/americas-cup-ac75-insights-from-a-vampire/

B. Ainslie. (2020, January 9). Road to the America's Cup podcast episode 5: Designing the AC75's hull. Retrieved June 4, 2023, from https://www.yachtingworld.com/americas-cup/podcast-episode-5-ac75-hull-design-124587

M. Fischer, B. Muyl. (2020, December 1). America's Cup: Two team designers analyse AC75 hull shapes - Tip & Shaft. Retrieved June 4, 2023, from https://www.sail-world.com/news/233558/Americas-Cup-Two-designers-on-AC75-hull-shapes

K. Chopra. (2019, July 13). *Understanding Intact & Damage Stability of Ships*. Retrieved 5 June, 2023, from https://www.marineinsight.com/naval-architecture/understanding-intact-damage-stability-of-ships/

C. Clarey. (2007, June 24). *Where the America's Cup First Set Sail*. The New York Times. Retrieved June 8, 2023 from https://www.nytimes.com/2007/06/24/sports/24history.html

Luna Rossa Prada Pirelli. (2021, June 29). *The design and construction of the AC75*. Retrieved June 8, 2023, from https://www.lunarossachallenge.com/en/news/785_The-design-and-construction-of-the-AC75

Howarth Corporation. (2017, May 17). *Sailing Theory Tutorials - Forces on Sails and Foils*. Retrieved June 8, 2023, from https://www.youtube.com/watch?v=NG5dCUA8HWg

The Editors of Encyclopaedia Britannica. (2023, January 12). *America's Cup yacht race and trophy*. Retrieved June 9, 2023, from https://www.britannica.com/sports/Americas-Cup

America's Cup. (n.d.). *WHERE IT ALL BEGAN - A RACE AROUND THE ISLE OF WIGHT*. Retrieved June 9, 2023, from https://www.americascup.com/history/1_WHERE-IT-ALL-BEGAN-A-RACE-AROUND-THE-ISLE-OF-WIGHT