Diplomarbeit

Solar and Wind Powered Boats - A Proof of Concept for the Extraordinary Volitan Yacht

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Wien, im Mai 2020

Simplicity is the ultimate sophistication.

Leonardo da Vinci

We can't direct the wind, but we can adjust the sails.

ARISTOTLE

Eidesstattliche Erklärung

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Wien, am 20. Mai 2020

Gencay Aslan

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Kurzfassung

Im 21. Jahrhundert nimmt die Bedeutung von Öko-Innovationen für Logistik und Transport aufgrund der globalen Erwärmung zu. Das solar- und windbetriebene Bootskonzept ist einfallsreich bei der Lösung des Problems der Kohlenstoffemissionen.

Das Ziel dieser Arbeit ist es, den Aspekt der Mechanik und Strukturen des Konzepts von Volitan Yacht Design, auch der Solar- und Batterietechnologie anhand von verständlichen Beispielen der Konzepte und verschiedenen Zeichnungen zu erklären. Nach einer klaren und prägnanten Erläuterung der Aspekte werden die Möglichkeiten zur Entwicklung eines Designs in diesem Bereich aufgezeigt, um die Investoren in die richtige Richtung für einen effektiven Start zu führen. Mit dieser Absicht untersuchte diese Studie auch die Software für Computer Aided Design und Computer Aided Engineering wie CATIA- und ANSYS-Software.

Schließlich habe ich alle Aspekte, die ich in dieser Arbeit behandelt habe, angewendet, um einige Teile des Volitan-Yacht-Designs zu analysieren. Es ist eine luxuriöse 32 Meter lange Segelyacht. Sie hat zwei Wingsails, deren Oberflächen auf beiden Seiten mit Sonnenkollektoren bedeckt sind. Die soliden Segel können sich neigen und drehen, um den Wind einzufangen. Dadurch erhalten sie den besten Winkel und können Sonnenlicht mit dem Solarpanel in Elektrizität umwandeln. Das Volitan-Design hat auch zwei Verlängerungsarme unter den soliden Segeln. Ihre Hauptaufgabe besteht darin, die 200-HP-Elektromotoren auf jeder Seite des Bootes zu halten. Das x-förmige Segelboot mit den vier futuristischen Wings, zwei Wingsails und zwei Verlängerungsarmen, hat zahlreiche Preise gewonnen, darunter den International Design Award 2007 in der Kategorie Nautische Boote und Transport sowie den Green Dot Award 2008 in der Kategorie

Transport. Leider wurde das Design noch nicht produziert. Diese Studie untersucht die Vor- und Nachteile des Designs sowie die möglichen Rahmenstrukturen für die vier Wings und die Möglichkeiten, die Wings mit dem Yacht-Hauptrumpf zu verbinden.

Die folgende Liste enthält die wichtigsten bereits vorhandenen Forschungsergebnisse sowie die Ergebnisse, die im Zuge der Masterarbeit gewonnen wurden. Die folgenden Aspekte werden in dieser Studie genauer erläutert.
Das solarbetriebene Bootskonzept wird anhand anschaulicher Beispiele definiert und erläutert.
Informationen über Solarenergie und Batterietechnologie werden geteilt.
Das Konzept des windbetriebenen Bootes wird anhand vorhandener Beispiele definiert und erläutert.
Informationen über die Mechanik von Windlasten und die Struktur der soliden Flügel werden geteilt.
Das Volitan Yacht-Design wird definiert und erklärt.
Die Berechnungsmethoden im Engineering, die zum Entwerfen und Analysieren eines Produkts im Schiffs- und Bootsdesign nützlich sind, werden erwähnt und einige Softwareprogramme empfohlen.
Das Prototyp-Testverfahren für den Schiffbau im Vienna Model Basin LTD wird vorgestellt und die Extrapolation bei den Modellversuchsmessungen wird kurz erläutert.
Die 55 Teile sind in CATIA entworfen und vier Lagerkonstruktionen werden für die Analysen heruntergeladen und 2D-Zeichnungen für die Darstellung der Verbindungen erstellt.
Die Analysen des Volitan Yacht-Designs werden in CATIA und ANSYS durchgeführt.
Die Möglichkeiten, die zusätzlichen Teile wie die Wings mit der Yacht zu verbinden, werden untersucht.
In der Masterarbeit finden Sie einen Entwurf der Rahmen und der oberen und unteren Wings.

Abstract

In the 21st century, the importance of eco-innovation for logistics and transportation increases because of global warming. The solar and wind-powered boat concept is ingenuity in efforts to solve the problem of carbon emissions.

The goal of this thesis is to explain the aspect of mechanics and structures of the wings, also solar- and battery-technology with good examples of the concepts along with lots of drawings, which are easy to understand. After explaining the aspects clearly and succinctly, the possible ways to develop a design in this field are given to lead the investors in the right direction for an effective start. With this intention, this study examined also the software for Computer-aided Design and Computer-aided Engineering such as CATIA and ANSYS software.

Finally, all the aspects, to analyze some specific parts of the Volitan sailing yacht design, are covered in this thesis. It is a luxury 32 meters long concept sailing yacht design. It has two wingsails and their surfaces covered by solar panels on both sides. The solid sails can tilt, shift and rotate to catch the wind and get the best angle to convert sunlight into electricity with the solar panel. The Volitan design also has two extension arms under the solid sails. Their main task is holding the 200 HP electric motors on each side of the boat. This X-shape sailing boat with these four futuristic wings, two wingsails and two extension arms, won lots of awards such as International Design Awards 2007 in Nautical Boats and Transportation Category, Green Dot Awards 2008 in Transportation Category. Unfortunately, the design has not been produced yet. This study investigates the advantages and disadvantages of the design as well as analyzing the possible frame structures for the 4 extensions and the possible ways to join them

to the yacht main hull.

The following list is the main researches and results that are presented in the master thesis:
The solar-powered boat concept is defined and explained with good examples that exist.
Information about solar power and battery technology is shared.
The wind-powered boat concept is defined and explained with good examples that exist.
Information about the mechanics of wind loads and the structure of the solid wings is shared.
The Volitan Yacht Design is defined and explained.
The computational methods in engineering, which are useful to design and analysis a product in ship & boat design are mentioned, and some software recommendations are made.
The prototype shipbuilding in Vienna Model Basin LTD is introduced and the extrapolation of model test measurements is briefly explained.
The 55 parts are designed in CATIA and 4 bearing designs are downloaded for the analyses and 2D drawings are created for the presentation of the joints.
The analyses of the Volitan yacht design are made in CATIA and ANSYS.
The possible ways to join the additional parts such as the wings to the yacht are examined.
The frame of the upper and lower wings are designed.

Chapter 1

Introduction

The production of sustainable travel options are becoming one of the central focuses of 21st century because of the climate change concerns. The main obligation to stop the climate change is the reduction of carbon emissions in almost all industries. For the same reason, renewable energy has become more promising as a good alternative for the systems, which are depended on oil to function. Eco-innovation for logistics and transportation has a very important role to achieve reduction in carbon emissions. For comparison, one large cargo ship emits the same amount of sulfur oxide gases as 50 million diesel-burning cars. It is because cargo ships use highly polluting fuel, which has around 3 percent sulfur [1].

According to the World Health Organization[2], the effects of air pollution result in roughly 7 million premature deaths each year, caused by increased fatal stroke, heart disease, lung cancer etc. Marina life is also affected by this issue. We see the short-term effects on marine animals such as skin irritation but we should be scared of the long-term effects.

Global Warming is a very important topic on the agenda of European Union (EU). If the European Council sets the EU on course to limit global warming to a 1.5°, the EU must present a vision that can lead us to greenhouse-gas neutrality by 2050 and commit itself for the big-M mission as it will be a very important mission [3].

The solar and wind powered boat concept is an ingenuity in efforts to solve the problem of oil dependency. Because of the growing awareness of climate change, use of application of clean and renewable energy is gaining more importance globally. Use of solar and wind energies are being developed as alternatives to fossil fuel. The solar and wind powered concept boats can be used instead of fossil fuel dependent sailing vessels. These are eco-friendly boats with almost zero emissions. The development in the technologies and the material-science allows us to design high performance, clean and inexpensive sea vehicles. These aspects make the solar and wind powered concept boats one of the best options overall.

1.1 An Overview of Solar Powered Boats

The journey for Photovoltaic (PV) boats started around 50 years ago but it took many years for their commercial use in a public transportation because of the high costs of materials and low efficiency of the technology those boats have. However, the idea of generating energy while being on the water was a new and innovative way to reduce carbon emissions. That is why the idea is still alive and every day there are new developments in order to lower the cost and improve efficiency.

From the Research [4] they stated the users need to be satisfied with the three main factors; boat speed (maximum speed), weight (boat weight + person capacity) and price. Electric propulsion is the biggest problem.

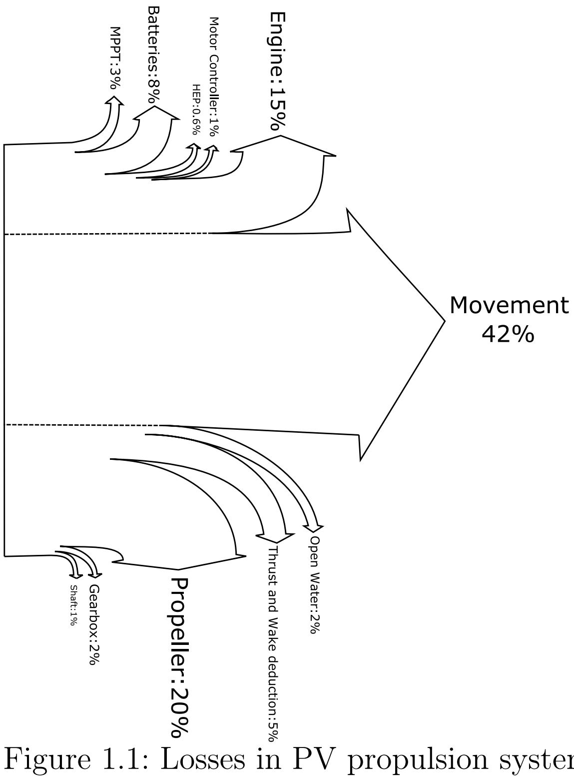

Figure 1.1: Losses in PV propulsion system for boats

At the beginning, most PV boats had a surface area between 5m^2 and 10m^2 for the solar panels. These surface areas could charge the batteries only for the weekends. The power was then drawn from battery packs, which were charged by solar panels. Without battery-power, the performance of the boats was really bad because the performances of the electrical engines were not matched with the offered electrical power from PV. You may say that boats with combustion engines have as well dimensioned engines and the application allows to reduce noise emission by operating the engine at a lower speed than the highest speed. But the aspect is not valid for electrical engines since they produce much less noise than a combustion engine. There is also almost 60% of ingoing power lost due to electrical and mechanical resistance when using the ingoing power in a modeled PV propulsion system to achieve the outgoing power used for movement. It means around 40% of ingoing power from PV turns into a movement. (fig. 1.1) With expanding weight, the losses increase too. Because of these big losses, we should take the PV integration into action at the beginning of the design process instead of retrofitting the boats with PV after they were designed and built. For example, a right hull choice for certain sailing circumstances is very important. They also categorized PV boats into five groups; boats for recreation, private purposes, transportation, racing, and research.

1.1.1 Solar Power

Sailors need electricity when they are sailing long distances for devices such as lights, navigation instruments, laptops, refrigerators or bilge pumps. On a sailboat, there are several ways to maintain power requirements. The best and most common way to provide power is solar systems. It can cover the entire demand for electricity and the battery-quest would be working as a generator. Let's look at its components to understand how the solar system works.

There are three components: the solar module, the charge controller and the batteries. A solar module converts light into electricity. The amount of electricity gain becomes greater if the sunlight exposure is stronger. Also with more solar modules, you can increase the charging current. After the solar module converts the light into electricity, the electricity will be used to charge the batteries.

A charge controller connects the solar modules and batteries. These controllers are developed just for solar modules. It regulates the charging current so it protects the battery from overcharging and over-discharging. On a normal yacht, there is a starter battery for the engine and supply battery block-power for the devices on the boat. In the PV powered boats, there is an electric motor battery instead of the starter battery.

The first step for the selection of a suitable solar system for a specific boat is to determine the need of output power and the purpose of the boat. If we have a PV powered boat with a 200 hp electric motor, the motor alone needs around 150 kW output energy to operate. Simply we can say that the unit of electric power 750 Watt is equal to one horsepower produced by an electric motor. You can get a maximum of 320 watt-hours from a solar panel with a size of 65 by 39 inches (17.6 square feet; 1.635 square meters) if that panel receives full sun for one hour. 320 watt-hours for a 17.6 square feet surface is really a small amount of output for a 200 hp electric motor. To fulfill the need of this motor, the boat needs an 8250 square feet solar module. The second step is to consider the area, quantity and intensity of the approaching light to the solar panels. The quantity of sun light changes depending on the region in the world. A power yield calculator, which shows the daily sunlight intensity, to calculate the energy a solar system can generate on a day. This calculation gives an average value that can be used in practice. However, the weather can change every day from a sunny day to a rainy day, therefore a large battery is always required to compensate for fluctuation. The last step is to select the module type of the panels and the installation location. The modules can be fixed on the deck or the hardtop, and also on the surfaces, which are additionally added to the boat such as bimini or sprayhood [5], [6].

The effect of shade on the solar panels can be significant for losing the power output. One solar module has a lot of solar cells, which convert the sun light to electricity. They are black square boxes connected with each other in series across solar panel. The entire module is as powerful as the weakest illuminated solar cell. For example, during a sunny day, if a small sheet completely covers even only one of the cells in the solar panel, it can reduce the entire solar panel's power output 90%.

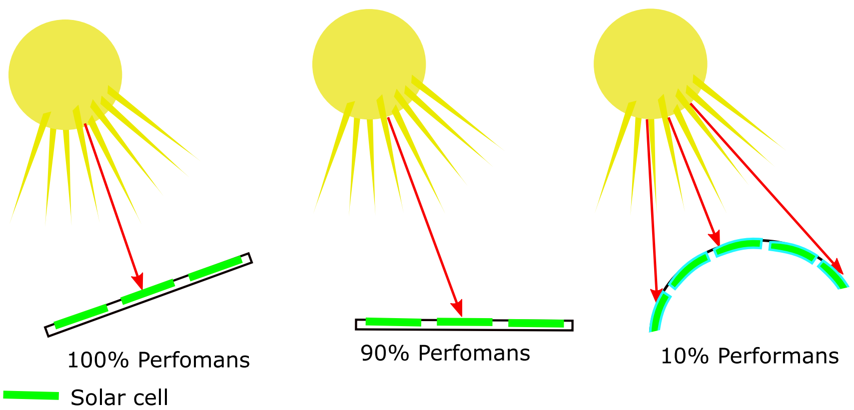

Figure 1.2: The Impact of Tilt Angle on Solar Panel

Another factor that dramatically affects the power output is the angle of incidence on the solar panel (fig. 1.2). The sunshine should strike on the panel at the right angle and hit all the solar cells, to get the best performance out of the solar module. Therefore, most of the solar modules have a flat surface to reduce the loss of energy. The changes in the intensity of the sunlight, which is shining on the solar panels, have a big impact on the power output [7].

1.1.2 Battery Technology

Boat batteries are as same as supply batteries, which are used for houses expect boat batteries should have vibration resistance and leak-proof cover, since a boat is constantly on the water. The rough conditions of the sea like big waves can cause problems if the battery is not suitable. This is valid, especially for the gel batteries. The high-quality deep cycle marine battery is one of the best choices in the market with its good range of ability to run down to a discharged state and then recharged. Nevertheless, we should avoid the lack of proper charging. As we all know using the battery until it is fully discharged and leaving it without charging again would decrease the battery life.

A good standard deep-cycle 12-volt battery with a 110 amp hour rating would work without any problem for a small-sized electric motor. [8]. But in this subsection, Tesla batteries will be mentioned because they could be the future of batteries. Perhaps, Tesla batteries are not yet the perfect fit for boat conditions. However, their technology in batteries is growing fast. There is a start-up about the electric boats with Tesla motors' drive-train technology. They planned to use Tesla's technology, which is already engineered and thereby, it has unlimited potential to grow [9]. If they develop a battery system just for boats, that could be one of the best choices to buy for electric boats in the future.

They also launch the battery recycling program throughout Europe [10]. We all know how important the proper disposal of dead batteries. It is very important that managing the battery recycling programs all around the world to avoid the danger of heavy metals and toxic chemicals in the battery get in contact with the earth.

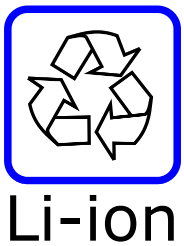

Figure 1.3: Recycling Li-ion

There are some examples, which we can find online the Tesla batteries in boats such as [11]. They are lithium-ion batteries and the lithium-ion cells will be better in the future.

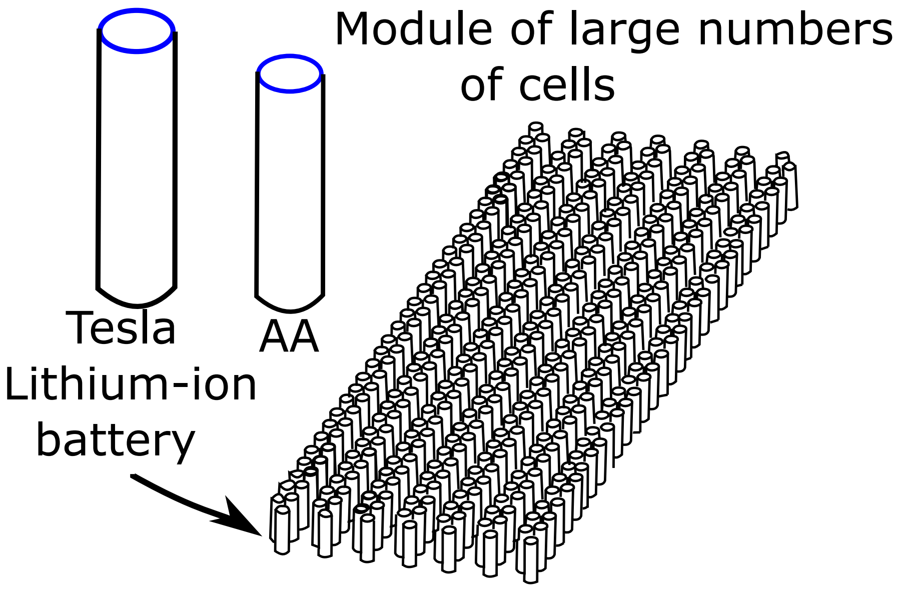

Figure 1.4: Tesla Battery

If we break open the Tesla battery cell, we can see different layers of components. The lithium-ion battery works on a concept, which is called electrochemical potential. The electrochemical potential is the tendency of a metal to lose his electrons. This concept is an old foundation. They developed the concept further to a point, that they achieved better performance with longer battery life, much longer than before. A standard Tesla battery cell is a little bit bigger than a regular AA lithium battery. Many of these small Tesla cells are connected in series and these series are lined up parallel with each other to build the Tesla module. These batteries produce a lot of heat during the operation. A battery management system maintains the optimum temperature and the other components to have a better performance. Also, the cooling technology in the Tesla battery pack manages the temperature. The cooling system is so effective, because of the small size of cells. This feature allows putting the cooling canals between the cells to transfer the heat directly from each individual cell. There are many other advantages of using many cylinder small cells instead of one big cell. By using many small cells Tesla got better results than other companies with bigger cells [12].

1.1.3 Examples of Solar Powered Boats

First public transportation PV boats, Solar Shuttle Boats by SolarLab (fig. 1.5) were built around 1998, which depend completely on solar power. And then there were lots of examples of Solar Shuttle Boats mostly for rivers and lakes and usually have between 15 to 30 meters long with the capacity between 40 to 120 passengers. These boats have the potential to act as solar power with their large surfaces for solar panels. For instance, the Hamburg Solar Shuttle can carry up to 120 passengers. It is a long boat with a 27 meters hull and its top speed is 15 kph. This boat is not only a sustainable ship, it can also act as a solar power plant [13].

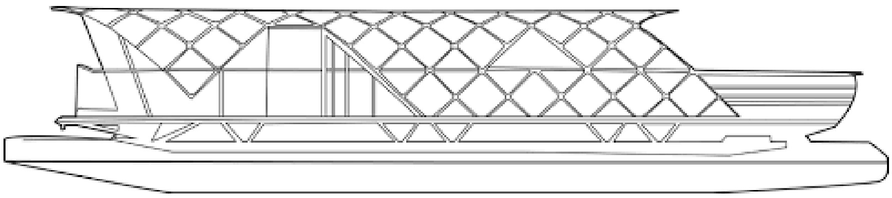

Figure 1.5: Solar Shuttle Boats by SolarLab [13]

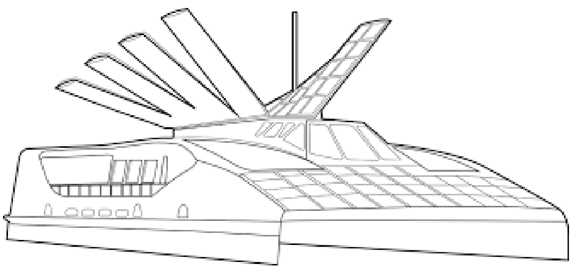

Figure 1.6: Solar Sailor by Solar Sailor [13]

Another good example of transportation PV boats is a hybrid ferry called Solar Sailor by Solar Sailor Company (fig. 1.6) in Australia. It is one of the first in his category, which achieves a speed of 11-kph by using solar and wind energy and while burning low-sulfur diesel fuel his speed can go up to 25 kph. Another feature in the design is the movable solid sails with solar panels and it allows catching the wind and sun to get better propulsion. This new class allows a 50 percent reduction of carbon emission while carrying 100 passengers.

There is also the PV boat: MS Turanor PlanetSolar (fig. 1.7), the largest and most famous PV boat, which is built in Germany in 2010 with the length 35-meter and 512 m^2 of solar panels. It has 26-kph as top speed and 9 kph as cruising speed. It is famous for being the first solar-powered boat, which circumnavigated the globe in 2012. It took 548 days with two 60-kW electric motors [13].

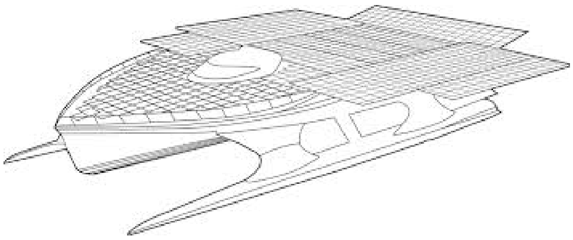
Figure 1.7: MS Turanor PlanetSolar [13]

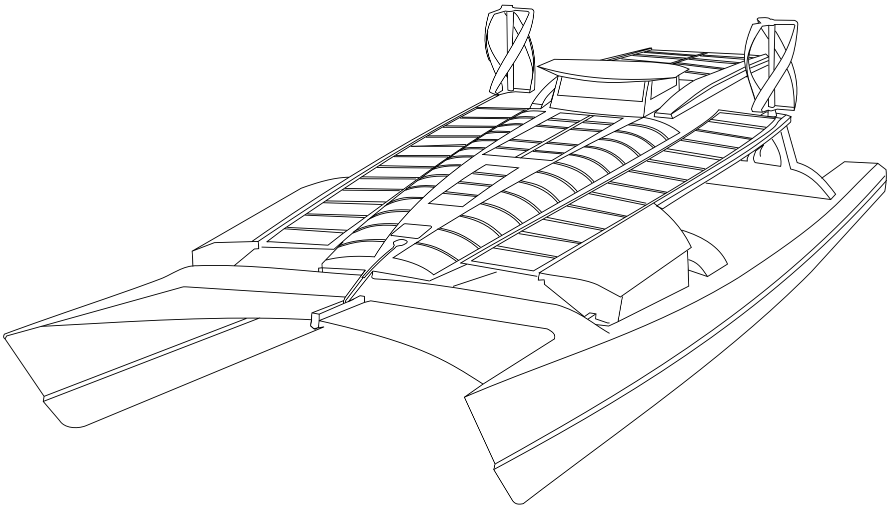
Figure 1.8: Energy Observer Ship

The first hydrogen vessel, aimed for energy autonomy. It means that the vessel can produce its hydrogen from seawater. The process begins with charging the batteries with solar panels. Once the batteries are full, the production of hydrogen will start through the electrolysis of seawater with the incoming energy from solar panels. As needed, the hydrogen energy will be used into electricity to prolong the energy autonomy. The battery-system will not be fully described here, as it will be discussed in the section 1.1.2. This design has 3 types, only with solar panels, with solar panels and wind turbines and the last type has wings(sails) instead of wind turbines. The one with wings sounds more reasonable than the one with wind turbines because the big wind turbines in operation would make lots of vibrations and it can affect the comfort of sailing negatively.

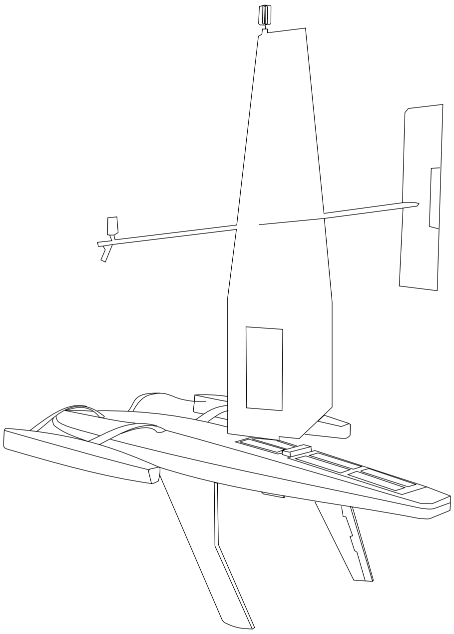

Figure 1.9: Saildrone by Saildrone

In “The Use of Saildrones to Examine Spring Conditions in the Bering Sea” [14] we see one of the best examples of research PV boat use to measure and understand Arctic warming, sea ice loss ,and ecosystem change. This program developed an unmanned surface vehicle (USV) and named it the Saildrone. (fig. 1.9). Two Saildrones USV, which are 5.8-m-long with twin outriggers and solar panels on the main body and on the 4-m-high wing. They provide their movement power from a solid sail (wing), which is linked to a solar-powered rotor to be able to turn itself along with vertical aches in order to set the optimal angle to the wind and they achieve sideways balance force with the 2-m-deep keel. They were in the 7800-km Bering Sea mission for 97 days. They transmitted data to shore via satellite and also provided an on-line user interface with time-series data downloading capability for every sensor including the four cameras they have. The Saildrone, Inc., as a provider company of high-resolution ocean data collected via these saildrones USV, announced on 17 May 2018 that it has closed a Series B funding round of $60 million to increase its fleet of USV to provide critical data for understanding the state of the planet in real-time. The total amount raised by the company is almost $90 million [15]. With this example, we see that a useful idea gets the attention and support it needs.

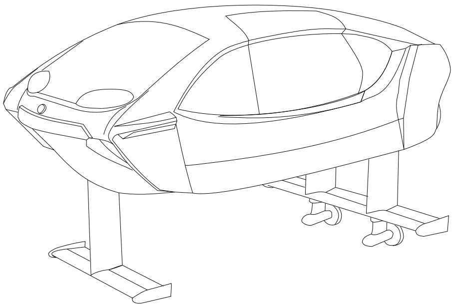

Figure 1.10: The Bubble by Seabubbles

There is another new innovation in zero emissions, 100% electric by French the startup named SeaBubbles, which is autonomous during its rides and charging, while stationed at the Dock. When passengers enter and take their seats into the Bubble (fig. 1.10), the doors will be closed and secured and it will get out of the Dock and ride to the target dock. Unlike the other examples, this small 5-meters boat has no solar panel on it but on the Dock, there are solar panels to charge the Bubbles, when they are at the Dock. It even creates energy from the power of the water and the wind, in addition to solar energy. So it is a different way of thinking where the big surface of a dock's roof has a solar panel surface instead of the boat's top. They promise 2h30 autonomy navigation which is long enough for transportation and they can charge the boat in 35 min with fast charges (400V). These features make the Bubbles next possible water taxis [16].

1.2 An Overview of Wind Powered Boats

The sailing experience started with hoisting a sheet as sail on a mast and allowing the force of the wind to push the boat in the direction the wind blows. The method was not useful because of two reasons. First, the faster you go, the less force of the wind pushes your boat. And second, you have to sail in the direction of the wind. In time, sailors found the way how to get more from wind than simple pushing.

The goal of this section is to understand the relationship between solid wings and wind. In order to do that first, we will be learning the mechanics of wind loads by starting with the windsurfing sails to understand the basics of the sailing condition and the sail forces during surfing/sailing. And then the sail shape importance will be discussed with wind turbines blades and America's Cup boats' solid sails to explain the design of the solid wings' structure to understand how to build light and sturdy solid wings. At the end of the section, we should be able to understand the meaning of wind-powered boats.

1.2.1 Mechanics of Wind Loads

In order to understand the mechanics of thrust, we will learn about the simple mechanics of windsurfing sails and wind turbines blades in this subsection. These concepts are chosen because they are the concepts that solid wings are used. To understand the simple mechanics of lift (force) we start with a windsurfing sail.

Sail works very similarly to an aircraft wing. The main difference is in the airplane the wings are placed horizontal to the plane to allow wind to push the plane up. On the other hand, windsurfing sail sits vertical on the board, therefore wind pushes the surf forward. The wind goes over the sail and that creates two main forces, lift and drag. Lift acts rectangular to the sail. It is the force pushing the board forward and is the same force to keep the airplane in the air. Drag pushes the sail in the same direction as the wind (so drag generally pushes the board sideways).

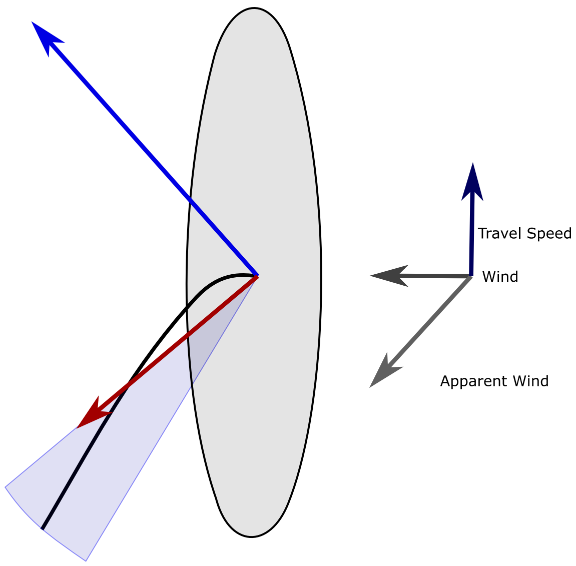

Figure 1.11: Forces on sails 3

By closing sail (increasing the attack angle) lift and drag forces will increase too. One theory says working range (attacking angle of the apparent wind direction) should be around 18 degrees in order to minimize the turbulent flow. The limited working range angle will be discussed in the topic of wind turbines. Because of the acceleration of the board across the wind, the true wind and the travel speed create a combined air flow called apparent wind (fig. 1.11). Every time when you are on a moving vehicle you feel the apparent wind. Apparent wind can be much stronger than true wind depending on the speed. At high speed, you can see the surfer has to counterbalance the high side force component (heeling force).

As we mentioned above surfers have to counterbalance the high side force by canting their rigs to windward. The equilibrium of force and moment (steady state of the system [17]) gives the equations to calculate the performance of a windsurfing or any other system such as a sailboat. The main difference between a sailboat and a windsurfing board is the mast of a sailboat is erected just about vertically on the boat, therefore the heeling moment is transferred to the boat. While this strong connection between sails and boat carries a big amount of load, the problem with heeling and pitch point comes up.

On the other hand, the sail of a windsurfing board is joined to the board by a universal joint, that is why the surfer has to balance the heeling moment with his body weight. All acting forces are transferred through the sailor to the board. The max speed depends on the maximal sail force, which can be calculated with the length of the wing, sailor's distance from the board and his body weight. The sailor is shifting his weight as far as possible to get maximal sail force. It means the heavier the surfer is, the faster he can surf. It means that this force is limited under any sailing condition.

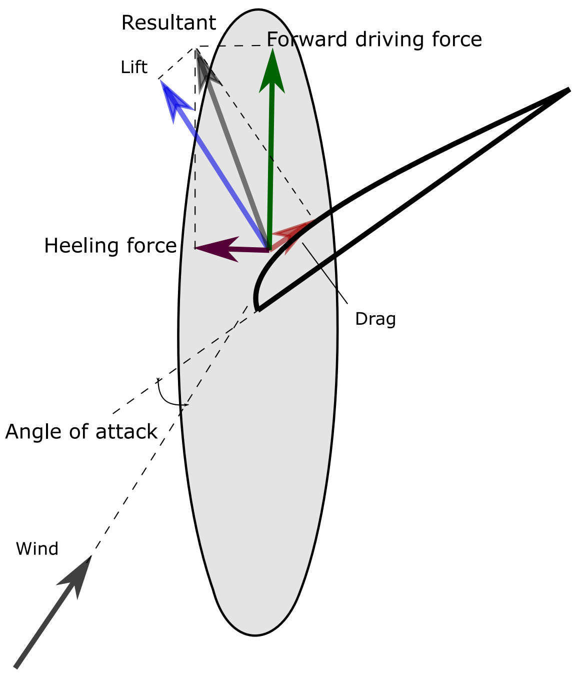

Figure 1.12: Surfing heeling force

It can be a little bit confusing with the component of the sail forces. We can see the connection between the forces in fig. 1.12 easily. Thrust and side force can be described as a function of the apparent wind angle. Because they are depending on each other, the angle of the apparent wind direction to the sail changes the thrust (forward driving force) dramatically. And the apparent wind calculates the ratio of board relative speed to wind speed. The sail forces change via sailing speed also via the angle of attack. The thrust reduces while the side force increases by the increase of board speed. The forward driving force (thrust) reduces with an increasing sailing speed when the wind blows at a constant speed. This physical effect is valid for all vessels moving with wind power. In short, in order to go faster sailor should be heavy but we can go faster by reducing sail drag (resistance) and the heavier the sailor is the greater the fluid resistance force(drag force) is. That is why there is no way to establish a great performance gain in a traditional way. Therefore the hydrofoils, lifting surface extending from the boats like a extended arm into the water, are created as a new way to reduce the drag force. They reduce the contract surface between board and water, which is called foiling to get higher speed. The hydrofoils designed to lift the board out of the water, when moving/foiling begins which prevents the water conditions affecting the speed of broad. Nevertheless, foiling has its downsides too. First of all, it is unstable, controlling a hydrofoil is very difficult. Thinking about foiling with 50 knots is scary, knowing that if the board touches the water surface at high speed you would end up in a catapult. There are good examples of how to avoid these problems. We will see them in the coming subsection. [18]

The weight of the fluid displaced by the immersed body is equal to the buoyancy. As we see in fig. 1.13 a tall thin block falls down from its first position after a small external force pushes it down for a second which unbalances it. That causes it to be unstable.

There is also the thicker block on the left in fig. 1.13 which is heeling over to one side but this time the momentum acts to right the block back up and keeps block floating vertically in the water. The reason for these two different results is the centroid of the area. In the first case with the thinner block, the centroid of area, which is underwater is on the left side while it is falling to the right side and it creates a momentum to pushing it to fall down. But in the second case with the thicker block, the centroid of the area is on the right side of the load force and that create momentum in the opposite direction to pull up the block to keep it in a vertical position.

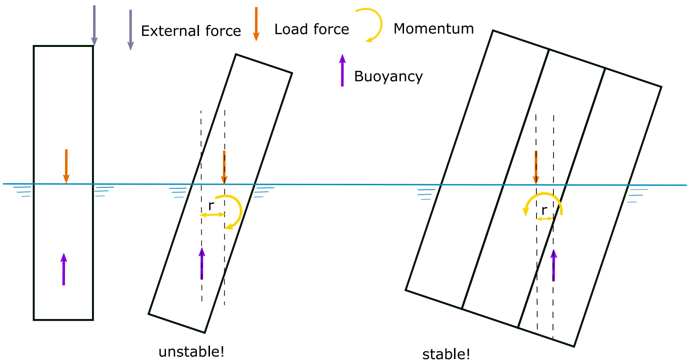

Figure 1.13: Buoyancy

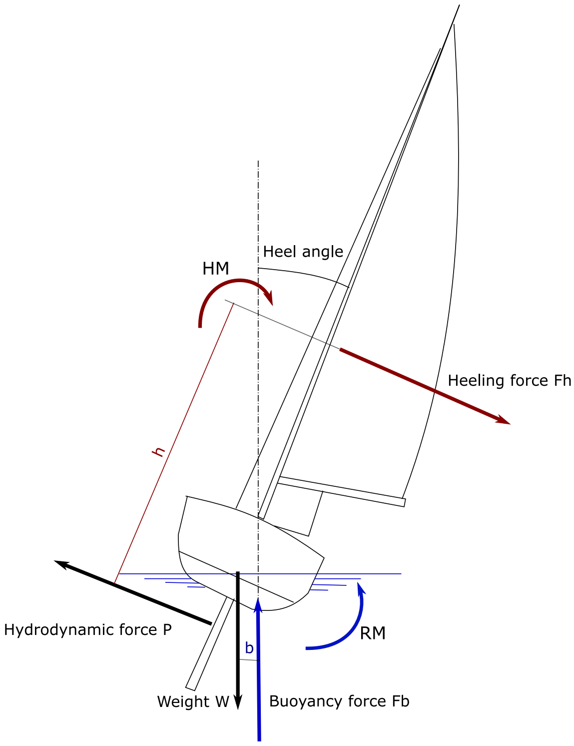

Figure 1.14: Forces in a sailing yacht

The sailboats reach similarly to the same situation with the thicker block. The difference is the heeling force acting on the big sails. Therefore, we need the long heavy keel to balance the heeling moment. We receive the hydrodynamic force from the keel and hull to have the equilibrium of forces (fig.1.14). The heel angle can be big and limiting to achieve the max speed of sailing on the regular sailboat at high speed [19]. And it is hard to sail with the hydrofoils on regular sailing boats. That is why it is more common we see the hydrofoils on catamarans than by regular sailings boat. And the reason simply is the width of the boat. The greater b distance (the distance between the center of the boats weight and buoyancy force) creates greater reaction moment RM against heeling moment HM. [20]

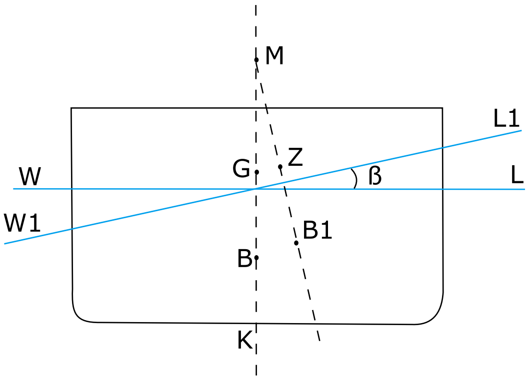

Figure 1.15: Metacentre and metacentric height

There is the measurement of the initial static stability of a floating body against overturning called metacentric height (GM). In fig. 1.15 9 shown the GM is the distance between the center of gravity of the vessel and its metacenter and B is the center of buoyancy. When the ship is pitted a little bit over, the original center of buoyancy is shifting over to the B1 here in fig. 1.15. And it turns up that the ship for small angles follows a circle and middle of the circle is metacenter M. It is an imaginary point, the ship rotates around. The larger the metacentric height is, the greater the initial stability becomes. But it is not always good to have a large GM because of travel comfort. A larger GM implies a shorter roll period in other words, higher acceleration by swinging to a side to the other side on the water. If you have a negative GM, your ship will slowly rock side to side, no matter what you do and it is not an ideal operating condition, you want to avoid that (fig. 1.16).

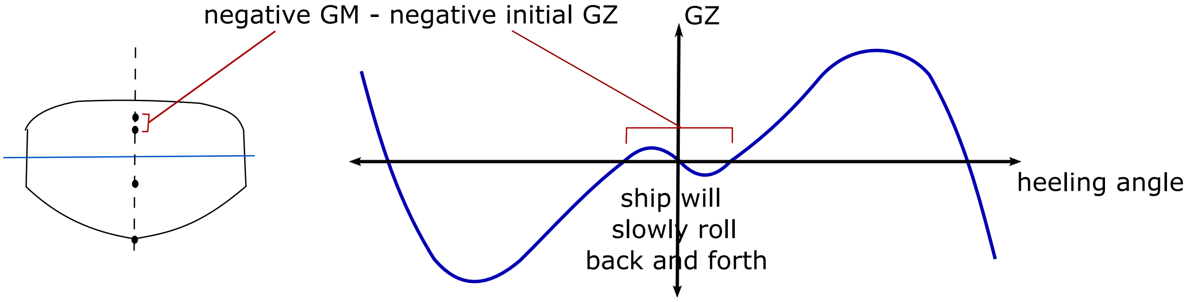

Figure 1.16: Negative GM

Other fields we can look at to understand the mechanics of wind loads with solid wings are wind turbine blades. The aim of the wind turbine is to convert the kinetic energy of the wind into electrical energy by converting the kinetic wind energy into mechanical energy. This can be done in two different ways. The first principle as mentioned at the beginning of the section (wind blows and pushes the blade in the direction it blows.) has poor efficiency and the second principle is the aerodynamic force principle, which is using by airplanes (as well as sailing/surfing). The constructive layout of today's rotor blades follows essentially the profile of the aircraft construction. So the blades of the wind turbine are shaped in a similar way to aircraft wings.

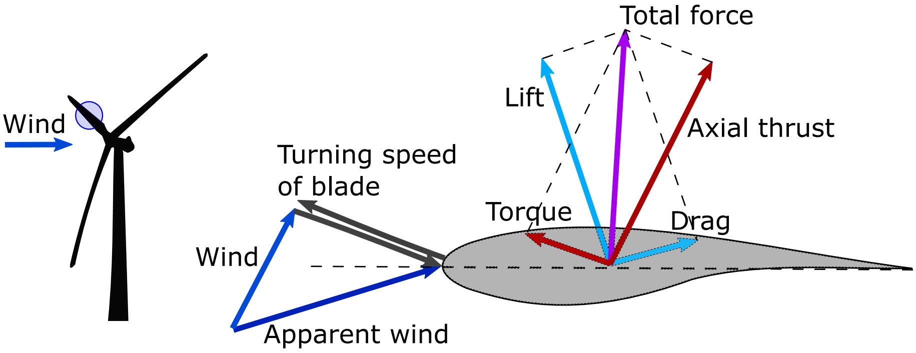

Figure 1.17: Aerodynamic forces on a blade

The principle goes simply, the airflow is faster on the top of the wing than on the bottom and it creates a higher pressure under the wing than over the wing. This pressure difference creates mechanical energy. This principle has a higher efficiency than the first pushing principle. According to Betz's Limit, we can converse 59.3% of the input wind energy. Actually in the field at first they used the airplane's wings and then after they found the funding to develop the actual wind turbine blades just for wind turbines. The efficiency differences were not that big after developing and using the new blades for the wind turbines [21]. Nevertheless, every research helps us to understand the world, we are living in. The forces, which are acting on the blade, have the same logic behind as the forces acting on the sail (fig. 1.17). The difference is, wind turbine blades are rotating rather than moving forward. That is why the turning speed of the blade is increasing along the blade. So the tip of the blade has the highest speed. Because the turning speed changes along the blade, the wind angle of attack changes too. That is why the blade structure rotates along the blade length in order to catch the apparent wind at the right angle. And there are three main sections along the blade; root section, cut through section, and tip section. The root section provides structural strength. Here the shape of the profile of the blade is not that important to be aerodynamic to catch the wind because of the slow apparent wind in this interval of length. The other two sections are getting more and more aerodynamical until the end of the blade.

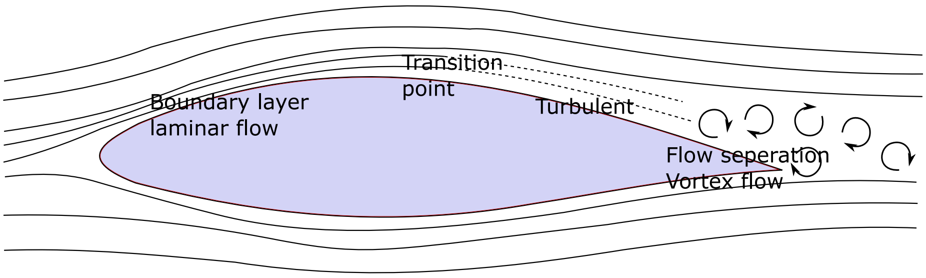

Figure 1.18: Blade cross section - Vortex

In fig. 1.18 we see basically why the pressure difference appears between under the wing and over the wing. We can put the condition of flow into two main groups as laminar and turbulent flow. The transition of laminar to turbulent flow calls as the laminar-turbulent transition. The Reynolds number is the main parameter for the transition. When the flow goes from stability to instability the transition starts. Briefly saying we want to avoid this transition, during converting the kinetic energy of the wind. Because the wind losses its energy into vortexes. This principle is discussed further in the section. In short, the speed difference causes the vortexes. The engineers are working to find the best shape of the profile of a blade in order to reduce the amount of turbulent flow. It is a tender work to achieve laminar flow. They realized even the dirtiness on the rotor blades causes a big amount of loss of converting energy via turbulent. The operation time of just a few months is enough to get enough dirty to affect the efficiency of the wind turbine. But in some situations we engineers want to have turbulent, for example mixing two gases together via turbulent flow. Before we start with the structure of the solid wings, for a better understanding of lift force, how the lift force is created by this pressure difference between over and under the wing will be briefly explained. According to Bernoulli's principle, faster-flowing air exerts less pressure than slower air under the wing. This pressure difference creates the upper force lift. But there is another explanation, which is based on Newton's rules. The key is the wing must reflect the air downwards and this can be achieved by increasing angle of attack or by using asymmetric wings. Air under the wing reflected down. Since the wind is slowed and reflected down by the wing, it pushes the wing up so the lift is created. This behavior of a flow can be explained both ways. They are just two different ways of looking at the same thing.

1.2.2 Structure of the Solid Wings

The discussion of the different rotor blade designs and material qualities has a long history but after many years of intensive development and testing, they found the modern rotor blades by using the fiber composite technology. The modern rotor blades will be mentioned here. In the last two decades, the blades are getting longer and longer to achieve better performance and to reduce the maintenance cost to the energy generation ratio. The modern wind turbine rotor blades are manufactured using fiber composite technology. They are made mostly from the fiber-reinforced composites via their large strength and stiffness to weight ratio. The composites consist of resin encapsulated fibers, which are arranged in a preform. The fibers essentially absorb the material tensions, while the resin takes on the embedding of the fibers and the formation of the shape. Basically, there is a variety of resins and fibers, which can be combined. The epoxy resin as matrix material has largely replaced the polyester. For very large rotor blades there is no alternative to epoxy resin. By selecting the fiber reinforcement, we can bring four factors to consider. The first factor is material. The dominant fiber materials are glass fiber and carbon fiber.

In Table 1.1, these two materials and natural fiber are shown with their conditions. Carbon is the most known one but if we compare it with glass, carbon's better mechanical performance should be balanced with its high cost. Overall it can be said, that carbon fiber is stronger than fiberglass. However, as mentioned before, strength and stiffness are two different things. Strength is the ability of a material to resistance to force. If the force is greater than the strength of the material, the material will break. So it only says under how much stress the material breaks. Stiffness is a resistance of how far a material stretch can. The less the material stretches, the greater the stiffness is. But it does not mean that stiff materials are strong. It brings to the next fact and that is elongation. Elongation is basically how far the material stretches before it breaks. If the material has more elongation, it can mean, it is tougher so it is not easy to break via its elasticity. Many people do not know this information and that is why they believe, that the carbon fiber is stronger than fiberglass via its low density and high stiffness. The stiffness of carbon fiber is comparable to the stiffness of steel structures and instead of steel, it is really lightweight. But in reality, E glass is widely used material for the consumer market and most economical. Their strength properties are extraordinarily good. Because, the manufacture of rotor blades from carbon fiber composite material is too expensive, carbon is therefore only used at the high stressed points of the rotor blades. For extremely large rotor blades with over 120m-rotor diameters, the use of carbon is necessary. Otherwise, the rotor blade would be too heavy.

Properties	Natural fiber	Fiber glass	Carbon fiber
Density	*Low*	*High*	*Moderate*
Stiffness	*Low*	*Moderate*	*High*
Tensile strength	*Low*	*Moderate*	*High*
Compression strength	*Low*	*High*	*Moderate*
Fatigue resistance	*Moderate/high*	*Moderate/high*	*High*
Cost	*Low*	*Low/moderate*	*High*
Energy consumption	*Low*	*Moderate*	*High*
Renew-ability	*Yes*	*No*	*No*
Recyclability	*Yes*	*No*	*No*
Accessibility	*High*	*High*	*Moderate*
Distribution	*Moderate*	*Wide*	*Moderate*
Disposal	*Degradable*	*Non − degradable*	*Non − degradable*

Table 1.1: Instructive comparison between different fiber materials. From [22]

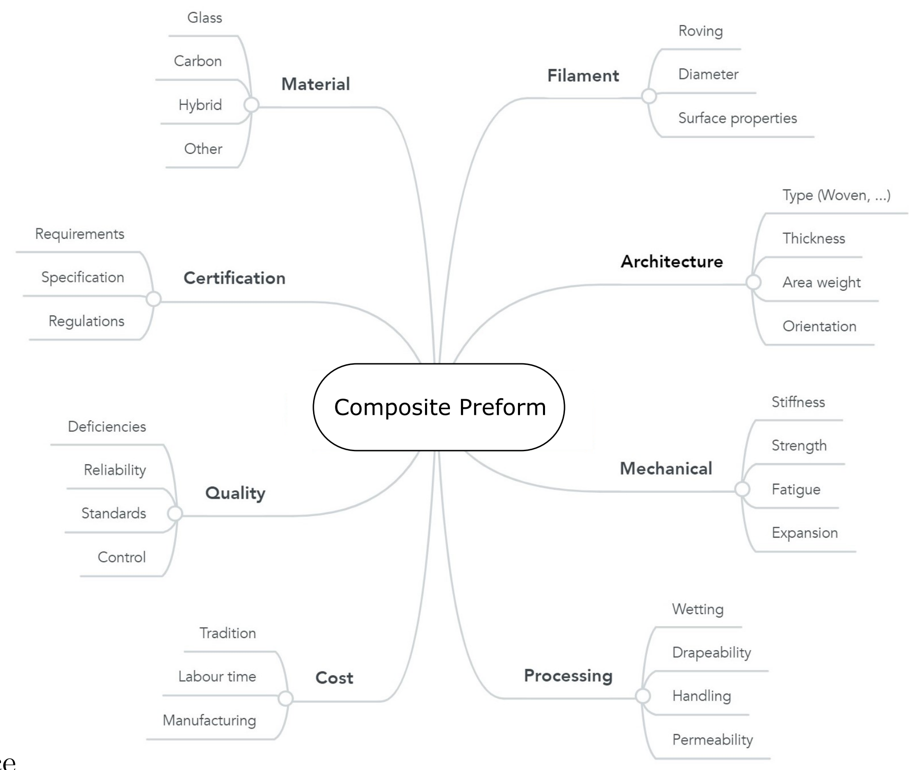

Figure 1.19: Aspects

It is possible to get better material properties by a combination of materials. That is why the combination of both carbon and glass is used for a better result of performance to cost ratio. Hybrid materials are coming into play with their good performance because they make effective use of the best properties from each material. But it is not an easy and cheap process and still needs many research and investment. Many stakeholders should work together to manufacture a new fabric, even though they have different interests. There are many factors, which should be in balance, it also involves many different engineering aspects (fig. 1.19). So the costs are important as the mechanical performance of the composites. Costs are sometimes even more important than any other aspects of the products.

Weight is the second topic, and the weight of the rotor blades is very important for the total tower head weight of a wind turbine. The mass of the blades is also a factor for the manufacturing costs. Furthermore, the mass of the blades can affect the aerodynamic design of the rotor. For example, the rotors at high-speed are intended to bend because of bending movements. Likewise, the weight of the solid wings is a very important aspect in the Volitan yacht design to decrease the risk of mechanical resonance. And if the wings are made of light material, they can be moved easily. Another factor that cannot be neglected is the bending elasticity of the solid wings. The elastic bodies absorb the fatigue loads better. If we need a lightweight material, carbon fiber is the way to go although its expensive price. Because the bodies, which consist of only glass fiber composite material, are relatively heavier because of the greater density of fiberglass compare to carbon fiber. If it is not that critical to have a lighter structure, E glass is the best choice, because of it's cheaper price. [23]

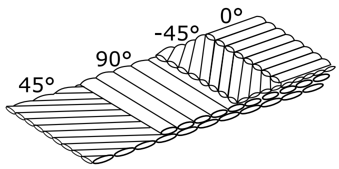

Figure 1.20: Angle of strand

The third factor is the direction of the strand of fiber. In (fig. 1.20) is shown the angle of strands and the direction of the strand of fiber matters. The mechanics of structure for the composition of fiber materials are very simple; the external moments can be transmitted in the perpendicular to the strand of fiber direction. The moments in the direction of the strand of fiber cannot be transmitted, because the resin is not as strong as fibers. Resin is used to fix the fiber in it's laid order by bonding the fibers together. If the fibers go in every direction, it provides equal strength in all directions. This condition of the multi-directional fabric also has the ability to conform to the shape of the mold better by allowing to shape compound curves much better than unidirectional fabric.

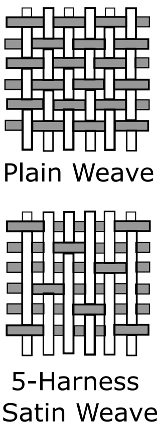

Figure 1.21: Weave

Fourth factor is the differences between plain weave and 5-harness satin weave. As we see in (fig. 1.21) by plain weave they are going under one strand and then over one strand, while by 5-harness satin weave they are going over 2 strands and under 2 strands. This is important, because weave affects the flexibility of fabric. 5-harness satin weave is easier to conform on curve surfaces than plain weave.

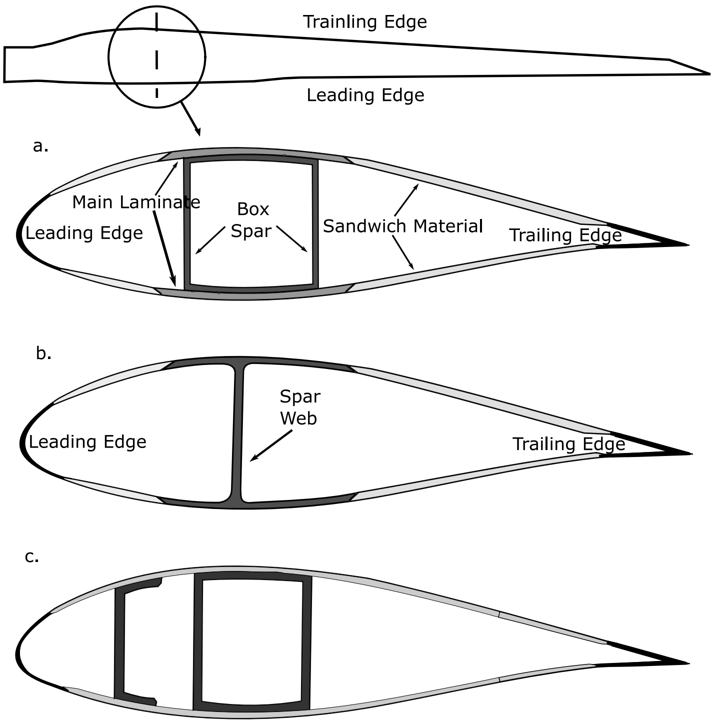

Figure 1.22: Blade cross section

The constructive layout of rotor blades can be divided into two static patterns. One of them is the continuous longitudinal beam with a box-shaped cross-section, which is dimensional in such a way that it can absorb practically all loads and it calls box spar. The spar is inserted and glued into the lower shell during manufacture so that the up shell can then be attached to the spar. The second one calls I-beam and in this case, the spar consists of only one or more spar webs, which can absorb the transverse forces and stabilize the shape of the shells. This method saves material and reduces weight, that is why in practice the two basic static patterns are often used in a mixed construction (fig. 1.22). For the support of the solid wings with their weight and expected stress of the wind, the I-beam with transverse ribs /metal wing ribs structure would be a good choice to use. The transverse ribs are necessary because the solid wings for a sailing yacht should be wider than wind turbine blades. The wings can be made of two main I-beam with the transverse ribs and they can be covered with some sheets of carbon fiber skin, which will give great strength to the wings. That is why using box spar instead of an I-beam would not have a significant advantage in strength and it adds the increased weight to the wings which would increase the possible problems mentioned above. The technique of laminating is a cheap way to manufacture outer rotor blades. The necessary prior condition for the laminating technique is the availability of a negative shape of the outer rotor blade contour. There are mainly four different manufacturing processes but only the vacuum infusion process will be mentioned here because it has become widely accepted. The process starts after inserting the mats. The rotor blade shape is sealed with plastic foils and then evacuated. The resin is pumped into the mold with the help of a pump and sucked in by the vacuum.

In this way, air bubble that can reduce strength are largely prevented. In addition, the harmful emissions of the resin are reduced. Normally, the lower and upper shell of the blades is made separately in the mold. After gluing the spar webs or the box spar into the lower shell, the upper shell is glued to the lower one. Also, the new processes can also make it possible to produce both shells in one process without a glue point (Siemens “Integral Blade”). [22]

The rotor blade technology will continue to have a decisive influence on the further development of wind turbines in the future. If the blades continue becoming longer, the transport and assembly problems will alone pose new challenges as new joining techniques for the engineers.

1.2.3 Examples of Wind Powered Boats

But there was one team, who were not afraid of catapult, and after their first boat was destroyed because of a crash, which ended up in a catapult, they found the funding and created a new vision into sailing. Sailrocket is a unique sailboat design and their success changed the wind-powered boats from the classic sails (fig. 1.23). One of the Sailrocket's feature is eliminating the heeling force. It has the simple principle similar to windsurfing. As we learned that the windsurfer is shifting his weight to balance out the forces. Once it reaches the equilibrium, there is no heeling moment on the board itself. Because of Sailrocket's complex design and her size, the problematic forces can be used for her advantage. And the design is ready to change the child's eye view of a sailboat. 12 years of effort brought them the first-speed sailing record above 60 knots with the speed 65.45 knots on 24 November 2012 (Wikipedia). The boat is like it reaches down from the air and touches the water. Its hull looks like an aircraft's fuselage and points in the opposite direction of the apparent wind in order to reduce drag. And the solid wing shape like a hydrofoil and act like one, but using the air as the medium to gain lifting and thrust. As we see it in fig. 1.23 the wing extension on the outboard end is one of the key fundamentals of the design to avoid the catapult by creating a lift force at the end of the outboard. Also, the main beam has an aerofoil and provides lift. The faster the boat goes, the greater the lift force becomes. Thus airspeed increases along with it. These two aerofoil sections achieve the equilibrium of the moment, which can cause a catapult. The floats have a special design to reduce drag at high speed. At high speed, the leeward float starts to fly and at low speed, it supports the boat. The main foil creates lift and side forces and that raises the boat at high speed and as the boat slows, it lowers the boat. As well it works as a regular keel or centerboard to conjunct with the wing. The sail side force and foil side force balance each other. There is just one hydrofoil to balance the sail side force and the reason is to achieve stability and also it is behind where the passenger sits to make sure when it loses control the hull will fall in front of the boat instead of falling behind by flying. And this design brought the idea of high-speed transport with only wind power. [24]

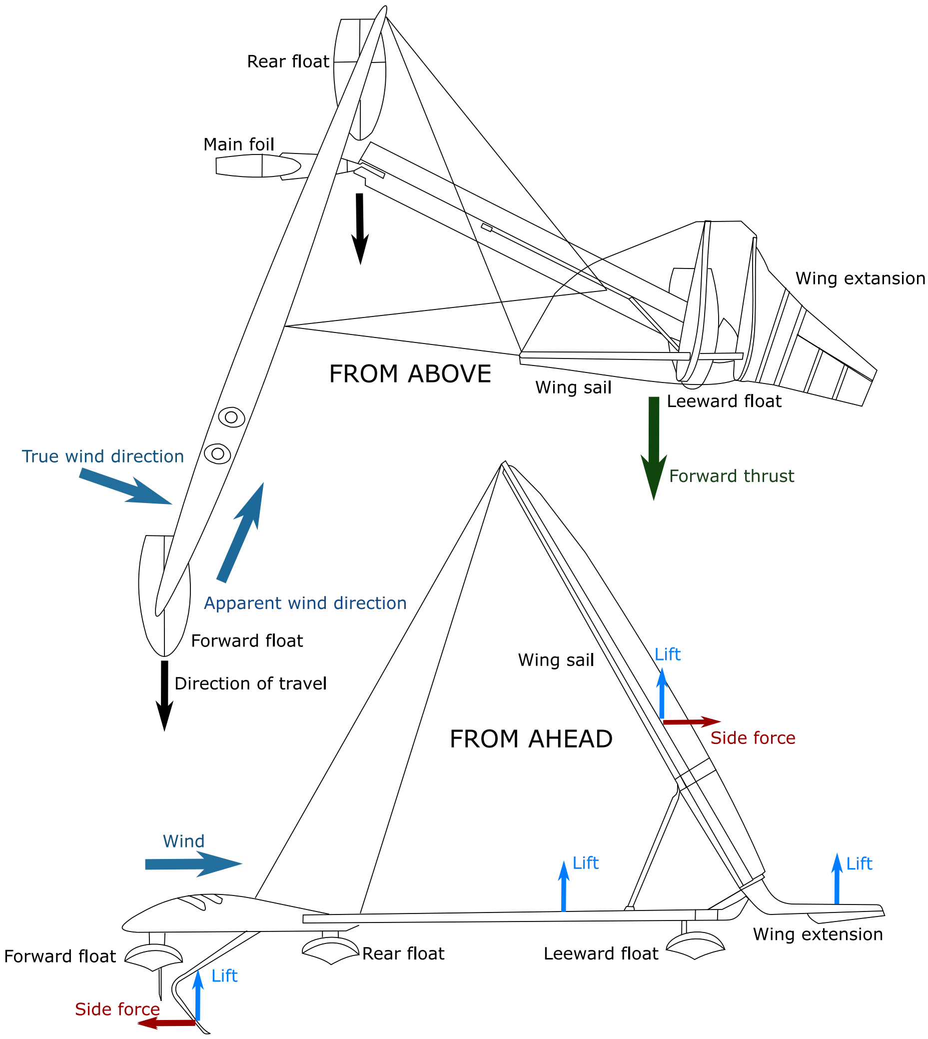

Figure 1.23: Sail Rocket

There is another good example of the concept of high-speed transport with only wind power and they actually traveled the world with high speed. It is called the flying boat and its name is Hydroptere. It is the fastest hydrofoil trimaran in the world. The trimaran "Hydroptere" broke many world records in its long service. Alain Thebault built the first model in 1987 to make his dream of flying over the water real. It was ready in 1994 and sailed for the first time. It was rebuilt several times to improve the boat. Now it reaches an average speed of over 51 knots over 500 meters and over 50 knots over one nautical mile. The Hydroptere broke the speed sailing record on 4 September 2009 with 51.36 knots (Wikipedia). They also intend to set a world speed record on the route from Los Angeles to Hawaii and they began with training to achieve the record. However, marine pollution on the route to Hawaii was a problem. Because the urban waste or the other kind of wastes on the water were dangerous at the high speed of hydrofoils. Their intention was the set a world speed record but instead of that, they called attention to the problem of oceanic pollution. Marine pollution is a real problem, which we all face. In order to find funding for the team, the team has published the Hydroptere 2. The designs reveal a relationship to modern offshore Tris. If enough money can be raised, the goal is the transpacific record. The mechanics of the boat is very similar to Sailrocket. The equilibrium of the moment is possible between the hydrofoils and sails. In fig. 1.24, we can see the main forces, which are acting on the boat. [25]

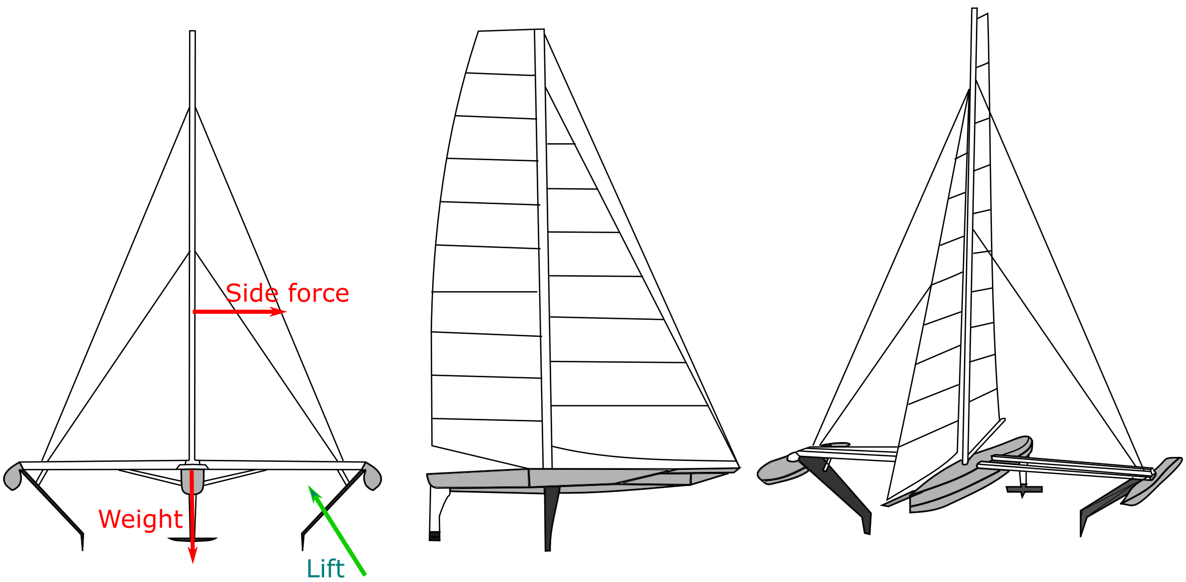

Figure 1.24: Hydrotere

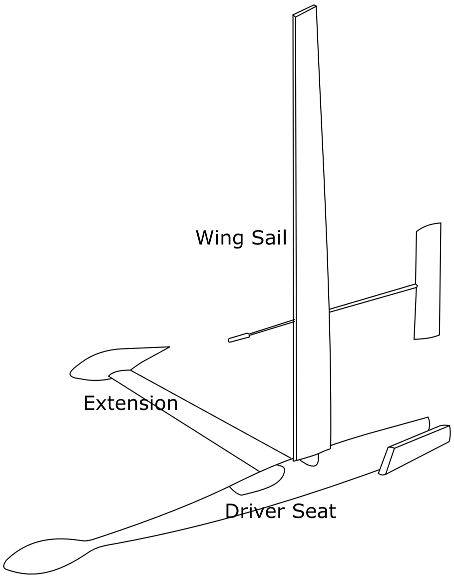

Figure 1.25: Greenbird

The energy company, Ecotricity is selling green energy to consumers and they are the ones who provided design inspiration for Saildrone [Section1.1]. They have some great projects such as the Greenbird. It is a wind-powered vehicle with no engine, which broke the land speed record for the fastest wind-powered vehicle with a peak speed of 126.1 mph (202.9 km/h) on March 26, 2009. The driver of the Greenbird said that he needed full concentration to keep the vehicle in a straight line at the maximum speed limit and it is quite scary. After breaking the world land speed record, now they want to take the ice record [26]. In fig. 1.25 we see the tall wing and extension to create the counter moment to archive the equilibrium of momentum at high speed. The wing sail system is used for the Saildrones wing (fig. 1.9).

The company Energy Observer was mentioned earlier and its three type boat; only with solar panels, with solar panels and two big wind turbines, and the last type has wings(sails) instead of wind turbines. This one with wings (fig. 1.26) is my favorite in these three types Because it gets directly drive force from wind, instead of converting the wind energy into electrical energy. In this process, there are energy losses and lots of vibration on the boat, while the turbines turning (fig. 1.8).

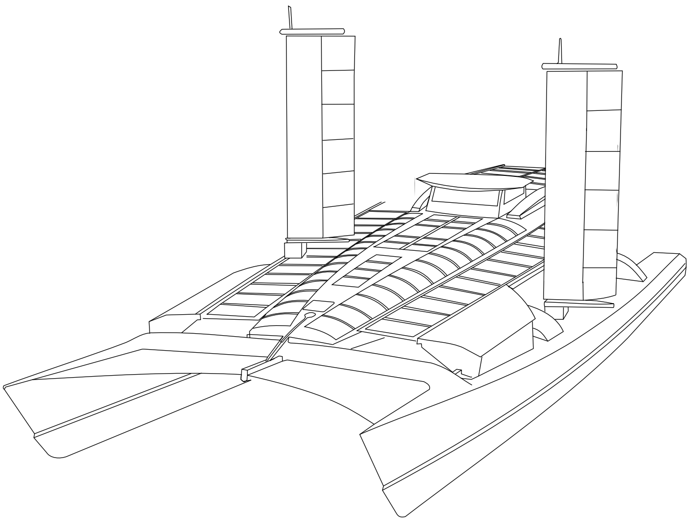

Figure 1.26: Energy Observer Ship 2

If America's Cup is not mentioned in this section, it would be an incomplete section. The 36th America's Cup will take place in New Zealand in the summer of 2021. This organization is unlike anything else in sailing. It is no longer just a sailing competition, but a competition in terms of management, technology, and innovation. A campaign costs more than 100 million Euros in a successful year. You cannot compare that to other regattas. America's Cup depends on the crew being perfectly coordinated. Because they rebuild the yachts after every development. The sailors are required to do completely different things mentally and physically. The race there often only lasts twenty minutes, so every move has to be perfect down to the last detail. Before the race, there are lots of engineers, who are working to design the yacht, which should be stable and achieves a consistently high speed. In the first phase, they continuously design aerodynamic and hydrodynamic models with all possible settings. So essentially their work consists of calculations on the computer. They have to consider the weather condition as well. And then they build the first boat. They collect lots of additional data after the training trips. With the experience of the first boat, they build the second boat. Usually, the second boat is used for America's Cup.

In the last two America's Cups, the catamarans were sailing with hydrofoils that seem to fly over the water on two small wings. Actually, the foil technology is more than 50 years old but they have further developed the concept of these foils and applied them so that catamarans can be equipped with foils as standard. These catamarans can sail almost ninety kilometers per hour, because of their significantly lower water resistance. For example, a five-meter catamaran has two square meters of surface underwater. If the catamaran flies over the water on his foil, the underwater surface is reduced to half a square meter. The other resistances are also important but the big change by the wetted surface brings great advantage.

This next race will be done with monohull (AC75) instead of catamarans (AC50). AC75 (fig. 1.27) is a 75ft sailboat class design. It has a monohull, that looks more like an airplane than a boat. There are two main differences between AC75 and AC50. On the monohull boats, the foils are away from the hull and it makes the acceleration difficult. The second difference between these two designs is the shape of the hull. Monohulls are simply more aerodynamic in the air than catamarans and can speed up to more than 50 knots. The first difference is not that important, because most of the time the boats will fly over the water anyway.

It seems like sailing will change a lot in the coming years. The teams in America's Cup get younger and younger every year to fulfill the need of faster reactions from the crew in the race.

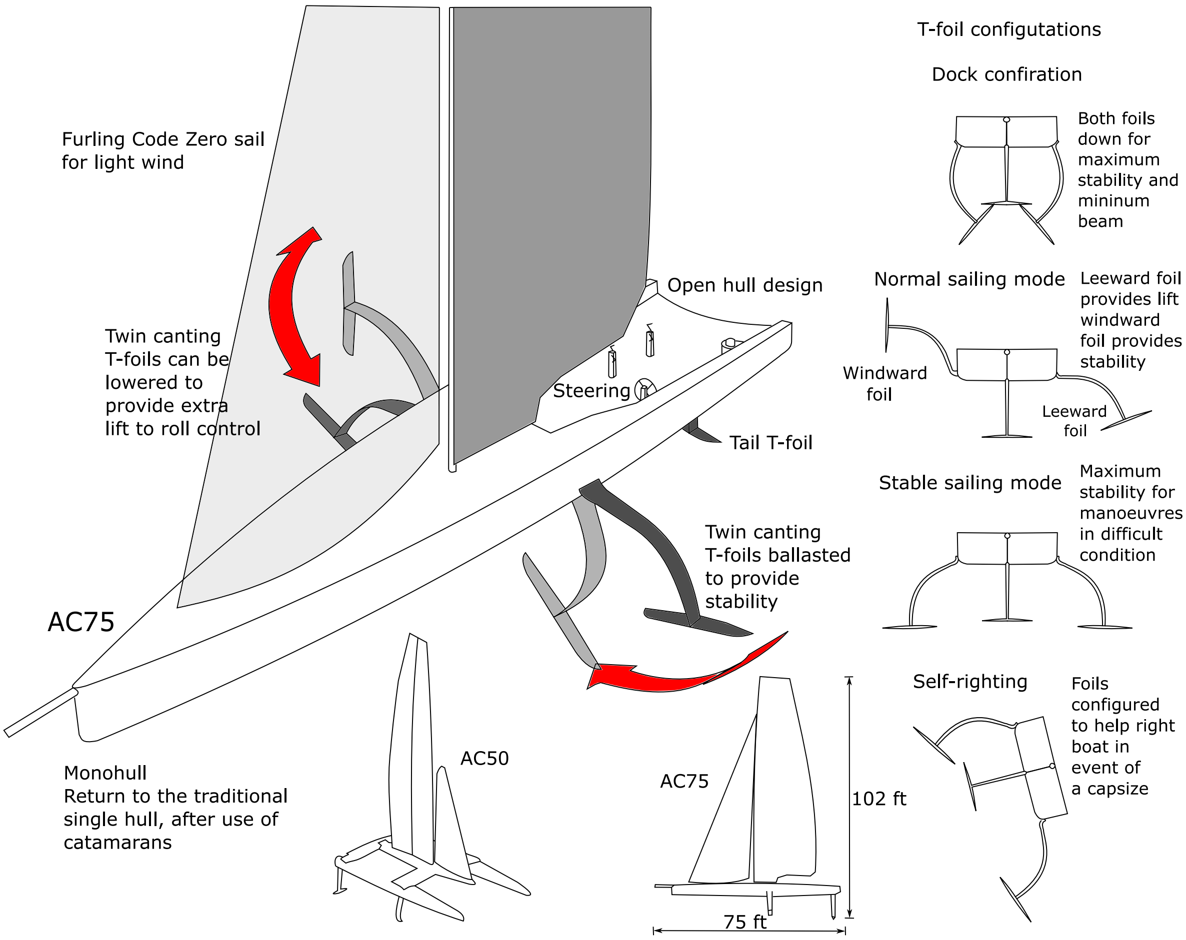

Figure 1.27: AC75

1.3 Solar and Wind Powered Boat Concept-Volitan

Volitan Yacht design (fig. 1.28) is an eco-conscious sailing vessel. The name "Volitan" comes from a flying fish, which lives in the Mediterranean sea. The name reflects the concept of the yacht, which can catch the wind in his solid sails to give momentum to the boat or if the wind is not cooperating, it can propel the boat with two 200 HP electric motors. Also, the design team is a Turkish design team from the Mediterranean-region, called firm Designnobis, who dreamed up a self-sufficient craft for the eco-conscious yachting class.

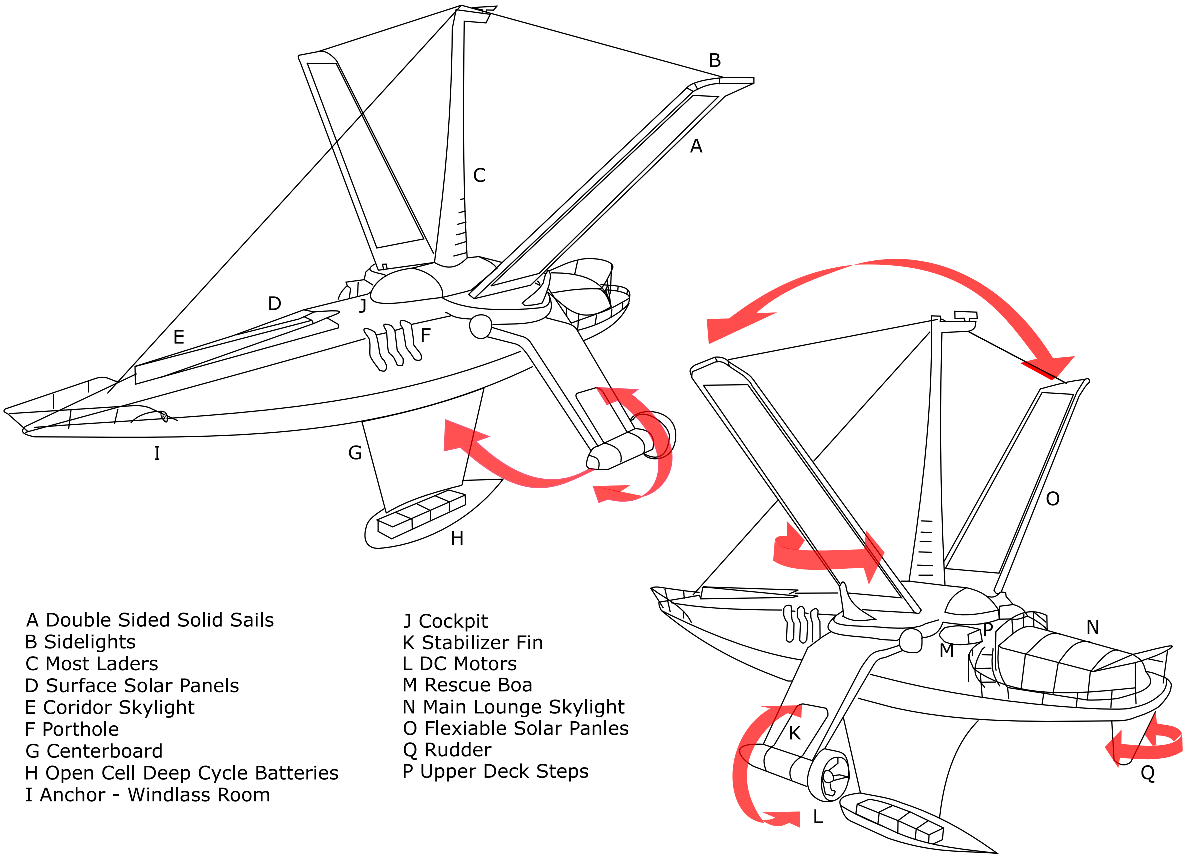

Figure 1.28: Volitan System Parts & Components

The Volitan is a luxury 32 meters long concept sailing yacht. It has two solar flexible PV panels covering on both sides of the fitted two solid sails with 300 meter-square surface area as active and passive collectors to power the yacht. Volitan's fitted solid sails can tilt, shift and rotate to catch the wind like a traditional sail. These movements are controlled by an on-board computer. The sails mobility also allows tracking the sun to get the best efficiency of solar-panels exposure. There are also lower extensions/wings underneath of each sail which submerge in the water with 200 HP electric motors at the end of them. The location of the motors allows the boat to turn around with a minimal turn radius. These two smaller wings are able to rotate too. Depends on the situation, they can fold up to lower the resistance or fold down to provide stability. They even have stabilizing fins, which can also rotate out to operate safely in wind up to 60 knots. It has average speed of 12-14 knots per hour with 18 knots top speed. Upper wings and lower wings create together an X-shape in a diagonal position. The expectation with these features is to be able to reduce aero- and hydrodynamic resistance and increase stability and efficiency. The X-shape can promise a better mast/hull length ratio than one tall solar wing design.

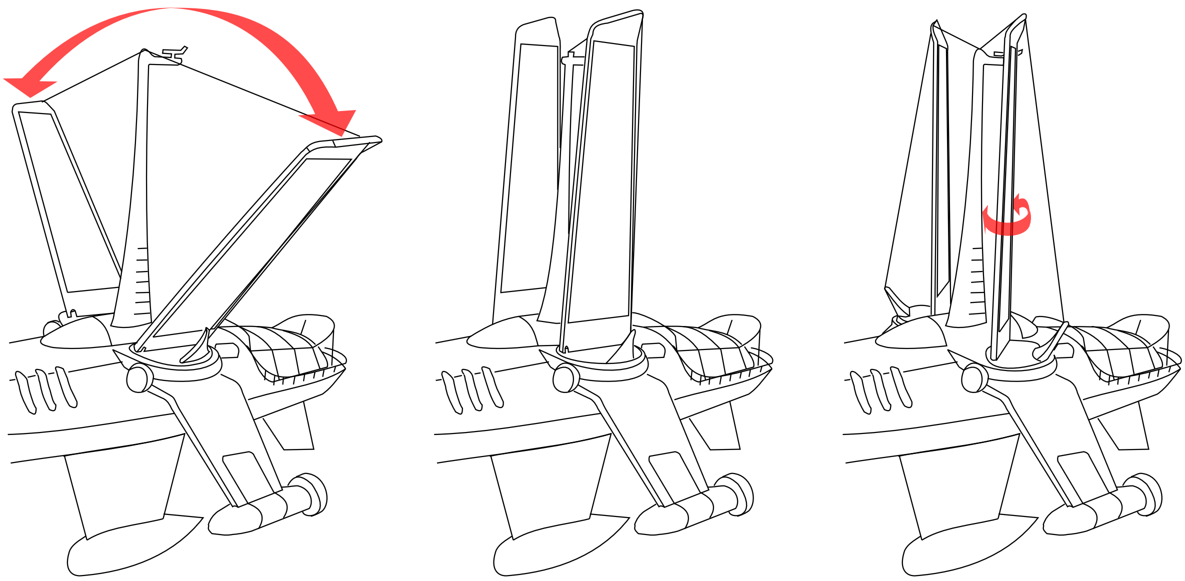

Figure 1.29: Solar Wings Movement Capabilities

These features make the design so special and allowed it to win lots of awards such as International Design Awards 2007 in Nautical Boats and Transportation Category, Green Dot Awards 2008 in Transportation Category. Of course, the sexy look of the boat attracted the people's attention too. In 2007 the Volitan was a futuristic symbol of raising awareness of environmentally friendly boats, which does not produce carbon dioxide emissions. Using sustainable resources is becoming more important. The solar panel fitted solid sails allow to use of the wind and solar power on the sea to propel the yacht while storing the energy in its batteries which is one good way to go with sustainable resources. It creates an estimated output of 8-10 kW. Now you may think that sailboats are already pollution-free but it is not true because they need their outboard motors to get in and out of the harbor. And the captains of the sailing yachts are using these outboard motors beside berthing often. This Design "Volitan" is the solution to make boating clean again by envisioning engine-assisted boat that does not burn a drop of fuel.

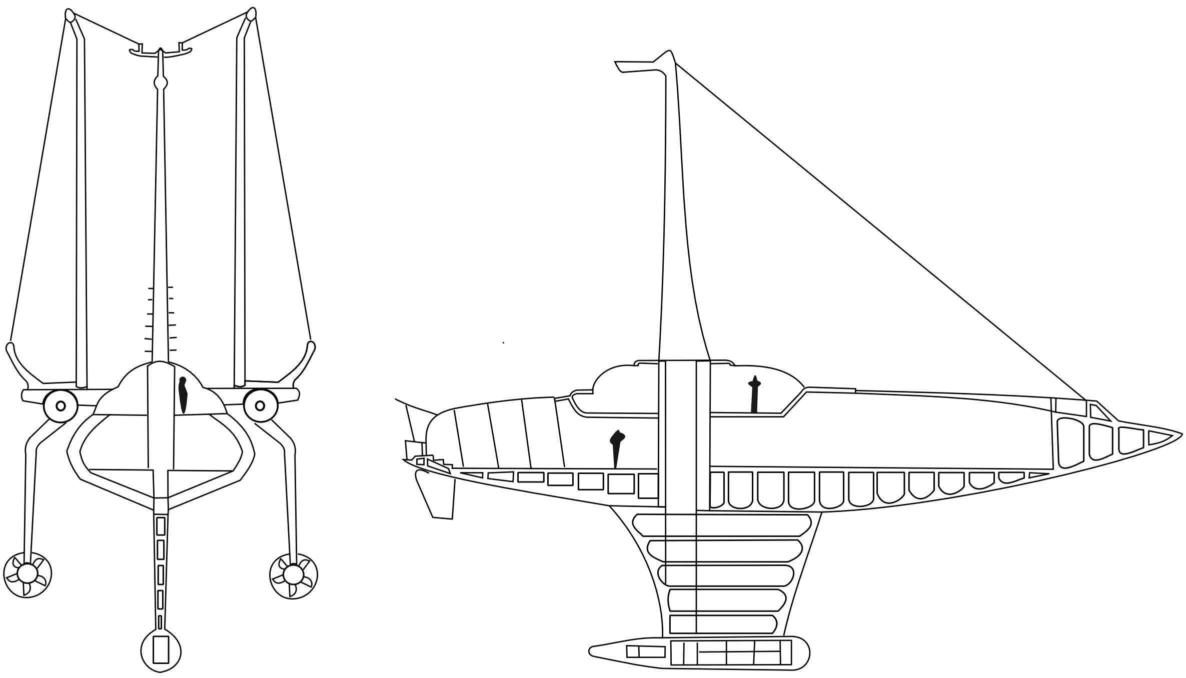

Figure 1.30: Volitan Section Views

Unfortunately, Volitan yacht has not been built yet, even though the design has been published in 2007. It is still just a concept. [13]

1.4 Objective

I wonder why any company did not dare to produce the sexy looking eco-friendly Volitan yacht design. I met the design for the first time when I was in high school. I was 17 years old yet and was fascinated with the design. I told myself, that I want to design a vehicle, which is as eco-friendly and cool as its design. At that time they told us, that the team, who designed it, won lots of awards with it. As a high school student, I decided I want to study mechanical engineering and to become a creative product development engineer. The dream brought me up to the Technical University of Vienna to get a good engineering education in German. During my study, I invested my time to learn as much as I can, so I can become a creative engineer in the future. Thanks to my thesis supervisor Prof.Dr. Manfred Grafinger my dream came true and I am analyzing the Volitan yacht design after many years.

The reality is not as beautiful as it sounds. The designs, which are very famous in the category of eco-friendly designs and win tons of awards in green design competitions as an example of Volitan design, cannot find funding to build the actual design. Usually, the eco designs, get the attention on the stage but in the real market because of their large cost to performance ratio, they do not get the same attention as they do in green design competitions.

My intent in the introduction chapter is to give an overview of solar and wind-powered concept boats. We went through the solar-powered boats as well as short tutorial about solar power and battery technology. And then we learned some good examples of the wind-powered boats with the short tutorial in mechanics of wind loads and structure of the solid wings. In the end, I introduced you to the Volitan Yacht design. The reason for having these short tutorials is to have an engineering viewpoint before we can talk about a functional design. End of the thesis in the last chapter, we will talk about the possibilities to implement the information we learned in this thesis into a useful design, which would make sense in the heart of people and also in engineering aspects.

Instead of focusing on how nice the design of Volitan Yacht sounds, the joints holding the four wings will be analyzed. The optimum inner structure of its wings will be concluded via using the Topology optimization, and the structure stresses under external load will be calculated via using the finite element method in Catia and Ansys software. The results of the analysis will give us valuable data to have an idea of the production difficulties of the X-wing fighter. The moment of inertia and the natural frequency of its parts will be calculated to perceive the advantages and disadvantages of the yacht. Additionally, some possible ways will be given to achieve the mobility of the four wings, which is promised by the designer.

To create functional products, we engineers follow the engineering design process, which is a series of steps (fig. 1.31) Our global problem is climate change and one of the solution is the reduction of carbon emissions. In this thesis, it is narrowed to the theme "Solar and Wind Powered Concept Boats". That is why my research was basically in the circle of this concept only. In the first chapter, the developments of the concept of solar and wind-powered boats are presented, and the basic knowledge of the concept boats are explained with small tutorials and real examples to understand the facts.

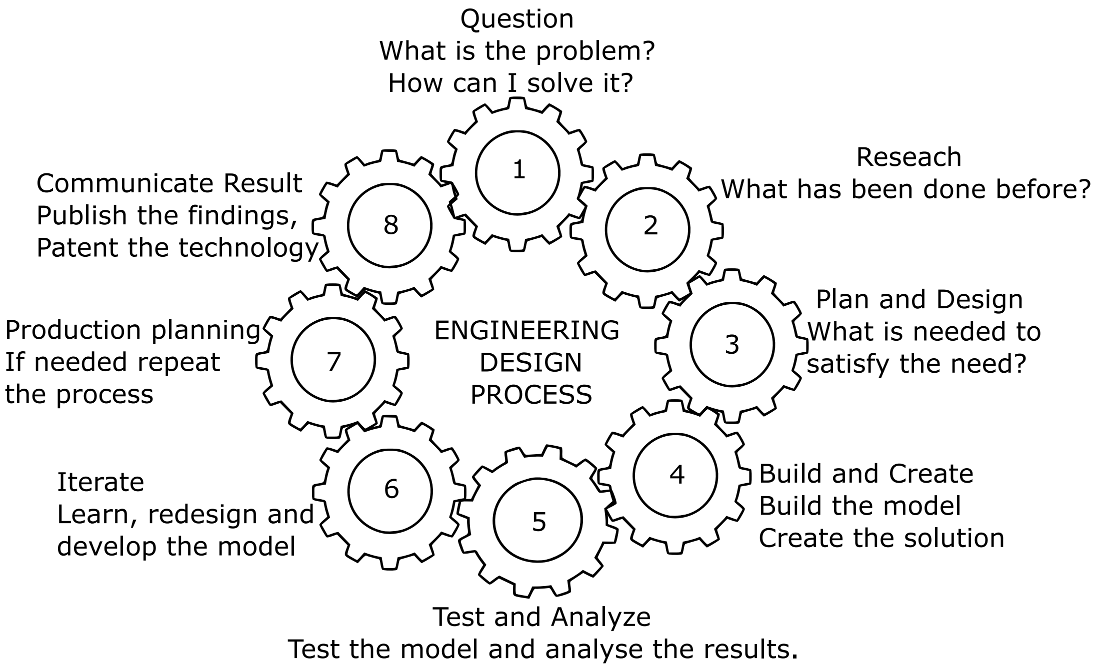

Figure 1.31: Engineering design process

This given knowledge should be a foundation for us to work on the first design of a boat model. The purpose of this thesis is to analyze the Volitan yacht design. The process of creating models to test and analyze in shipbuilding will be briefly defined before we have the results of the analysis. All the possible methods to develop a boat design are not done in this thesis, because it is a very long process to develop a functional design. It requests a team and capital goods to lead through all the processes.

Chapter 2

CAE-CFD-Modelling

The fundamentals of having successful products are as follows: having a high quality, establishing innovative technology, setting up customer-specific variability, offering the competitive price and being distinctive. These fundamentals request an interdisciplinary team of experts to bring the know-how into the company. And in the international market, everything must be ready right away. That is why the processing speed has a big impact to have a stable place in the world market. The technology is developed to be faster in order to speed up the manufacturing process. The computers, our cellphones, and even our daily life are getting faster. This aspect is upgrading the competition between the companies especially in software. The product design quality and expression determine the market success these days. In view of this, the software importance is unquestionable. If a company wants to keep up with this competition, it has to use the power of software.

2.1 CAE (Computer-aided engineering)

In the modern product development process, different systems are required to work together. The systems are getting more complex and their parts numbers are getting higher. The interaction of these complex systems is the key to success. For example, the system simulations of product development for the automotive industry can be done professionally only by combining models for mechanics with those for electronics and software. The simulations can avoid errors by increasing product quality and save a lot of money and time for the company. These requirements can fulfill with the term CAE, Computer-Aided Engineering. In short, CAE is with the use of computers to design, analyze and manufacture products and processes.

A specific discipline within CAE is FEM (Finite Element Method). The FEM calculation or FE calculation is the method of FEA (Finite Element Analysis). It is a numerical method in which the structure is divided into the finite number of sub-areas (finite elements) to analyze the behavior of these sub-areas. The sub-areas can describe the continuum mechanical model easily by using algorithms. The sub-areas are achieved by meshing and meshing has limitations. The engineers should have basic knowledge of the capabilities and the properties of the different elements. To get a realistic model, geometric nonlinearity can be necessary and not all of the FEM software has nonlinear finite element analysis. FEM is used in structural analysis, heat transfer, fluid flow, etc. One of the most common ones is the stress and strain analysis.

With the help of FEM, they found a really useful method in lightweight technologies. The topology optimization is a method of CAE. Very early in the development process, the optimization software shows the engineers how the structure can be designed to reduce the used material but still meeting the expectations. Advance optimization targets can be minimizing stresses and increasing the stiffness.

2.1.1 CATIA Analysis

Catia is an integrated simulation tool in the early phase of development, which brings great advantages to the engineering design process. This assessing the variants quickly and efficiently allows choosing the right design very easily.

In Finite Element Analysis (FEA), the analysis can create better solutions with finer Mesh inputs, which can give results closer to the real value. The finer meshes can be created in CATIA, but there is some other FEA software such as ANYSY, which has the topology optimization feature. This feature of ANSYS software will be explained in the next subsection.

2.1.2 ANSYS Workbench-Topology Optimization

Computer-Aided Methods are helping the engineers with new challenges as mentioned before. Nowadays the engineers do not need to be expert in optimization of the product design in the development process. They can define the optimization tasks with less effort than before by using Mathematical methods. The designers still need to have a deep understanding of the processes in the FEM to be able to interpret the results in a meaningful way. Once they determined the goals of design and defined the manufacturing restrictions, the optimization algorithms automatically adapt the design to these requirements. These Optimization methods were developed through many years of hard work of engineers, who are expert in the field.

Figure 2.1: ANSYS

ANSYS software is a finite element software, which offers solutions for almost every CAE applications. The first version of ANSYS was developed in 1980 and after it was sold in 1994 for ANSYS, Inc. It is the largest independent manufacturer of simulation technology for numerical simulation in CAE. Its one of the biggest features is its ability to solve non-linear problems besides linear problems in structural mechanics, fluid mechanics, Temperature fields, electromagnetics, acoustics, etc. There are two versions as ANSYS

Classic and ANSYS Workbench.

ANSYS Workbench has improved algorithms for creating meshing, contacts problem, and interfaces in CAD systems. Entering the calculation problems is also easier with ANSYS Workbench.

The topology optimization is one of the computer-based calculation method, which can determine a favorable basic design (topology) for parts under mechanical stress. If the topology optimization is done at a very early stage in the design process, it gives the engineers more time to concentrate on the results. After the design is optimized, there is a probability of failure. If you optimize a simple structure, you will have a robust design optimization. If you optimize a complex structure, it is a high possibility that you will have a more complex structure after the topology optimization then before. There are some developments to solve this problem and they are getting really good results.

In fig. 2.2, we see the result of an example of topology optimization. We have a block here that is clamped from one side on an immovable wall and pushed down with an external force from the other side. The result is a little bit complex for a simple block problem. After this result, interpreting and reconstructing the structural topology optimization is necessary to have a clean CAD model. This can be done manually or semi-automatically. As we can guess the semi-automatic reconstruction takes much less time than manual CAD reconstruction.

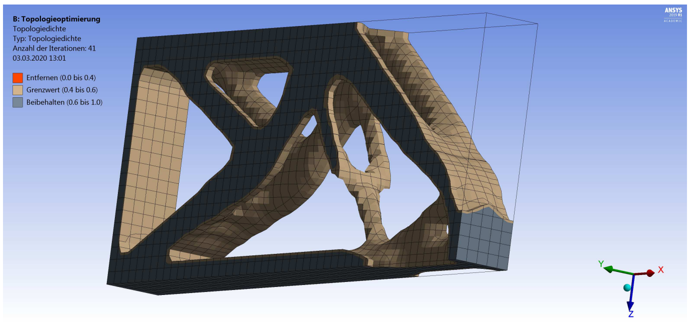

Figure 2.2: An example of a topology optimization

Manufacturing of these complex products is no longer problem for 3D-printers. These kinds of complex structures will be manufactured more often in the future, related to the reduction of the costs of 3D-printers. [34]

2.2 CFD (Computational fluid dynamics)

Computational Fluid Dynamics (CFD) is a confirmed method of fluid mechanics. In simple words, it predicts the behavior of fluids via calculating equations. It uses numerical methods to solve fluid mechanics problems with Navier-Stokes equations, Euler equations, and the potential equations. The Navier-Stokes equations are the most complex and comprehensive in those equations. The Navier-Stokes equations consist of the Mass balance equation which is also called as material balance equation, pulse balance equations in the x,y,z direction, or Energy balance equation. They are non-linear partial differential equations of the 2nd order. These mathematical methods describe the behavior of a fluid (liquid, gas or accumulation of moving particles). High-performance computers are needed to solve the partial differential equations if the turbulence and the hydrodynamic boundary layers are involved. You can set up the mathematical model, if you know the properties of the fluid such as density, viscosity, etc. [35]

Aspects	CFD	Experiment
Costs	$Staff$	$Staff, Devices, Comsumables$
Needed Time	$Depending\,on\,Complexity$	$Depending\,on\,Devices$
(Spatial) Scale	$unlimited$	$exclusively\,Laboratoy\,Scale$
Information Content	$High\,(entirely)$	$Low\,(limited)$
Health Safety	$Fully\,Available$	$Depends\,on\,Conditions$
Accuracy	$High/Moderate$	$High/Moderate$

Table 2.1: Comparison Table between CFD and Experiment.

The motivation to solve these complex equations is having an inexpensive alternative instead of the water channel or the wind tunnel experiments for the calculation of important fluid mechanics problems such as the calculation of the water-resistance. If we call the CFD as a virtual experiment, in the comparison table between CFD and experiment 2.1, we can understand the motivation for CFD much better. The cost aspect is usually the determinative factor for the decision. The cost of a CFD simulation is just the personnel costs of engineers after the investment for the hardware and software. On the other hand, the cost of a physical experiment is much higher in most cases.

$$\text{Navier-Stokes Equations:} \qquad \frac{\partial \vec{u}}{\partial t} + (\vec{u}\vec{\nabla})\vec{u} = -\frac{1}{\rho}\vec{\nabla}p + \nu\Delta\vec{u} \tag{2.1}$$

$$\text{Continuity equation:} \qquad \vec{\nabla}\vec{u} = 0 \tag{2.2}$$

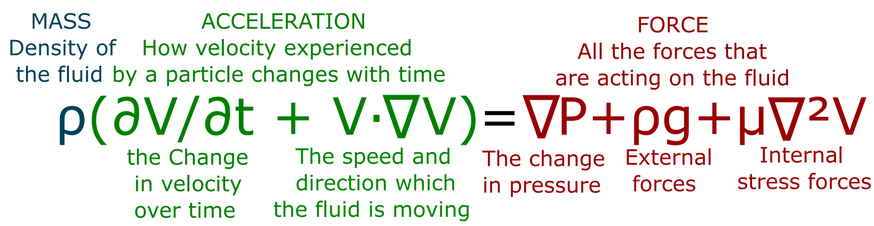

Figure 2.3: Navier-Stokes Equations - Describe the flow of incompressible fluids

Navier-Stokes Equations (2.1) are used with the continuity equation (2.2) together to solve the fluid mechanics' problems. In fig.2.3, we see the connection between Newton's F=ma and Navier-Stokes Equations. The term, acceleration has two components. If we describe the velocity in vector and the rate of change of the vector respect to time is giving the acceleration vector. A vector has length and direction. That means there are two aspects, which can change respect to time. So these are the change in velocity (speed) over time and the direction of motion. On the right side of the Navier-Stokes equations, we have the force and these are 3 components of the forces([36]). They can be explained with a simple example. In a moving car, if you pull out your hand through the car's window and the wind pressure you feel when you hold my hand's palm against the wind, is the first component of the force. If you hold your palm in the direction to the street, the pressure you feel is the internal stress forces, because the component is just depending on viscosity of the fluid. If you try the same thing in the water at the same speed, holding your hand in this position will be so much harder. We will start with the topics, the RANS-Reynolds-Averaged Navier-Stokes and LES-Large

Eddy Simulation before we go into much detail.

2.2.1 RANS (Reynolds-Averaged Navier-Stokes) equations

As mentioned CFD predicts the behavior of fluids via calculating equations. We can summarize the behavior of fluids in two aspects. Laminar flow and turbulent flow. Flows in the laminar phase are well ordered and the fluid moves in layers along continuous. On the other side, the turbulent flow is apparently irregular and disordered. It is almost a universal phenomenon in fluid mechanics. One of the main aspects that triggers turbulent flow is the velocity difference between particulars of the fluid. When the flow becomes turbulent, the Vortexes (Eddies) are created in the flow. The random vortexes continuously change and vary their size and shape. These continuous changes in flow increase the ratio of mixing in the fluid. Not just at the molecular level, but also at the energy and momentum level. So it also increases the diffusion coefficient.[37]

In simple words, the inertial forces in fluids create Eddies, if particulars of the fluid obtain a big velocity difference between them. The water flows on a still surface. Because of the velocity difference between water flow and still surface, the particles fall together and roll over just like we roll over, when the surface, which we are standing on, is moving independently than us with its own relative velocity. Of course, there are many more parameters and factors in this big and complex theory but at least this simple exemplary explanation can give us an overview of the mechanics of Eddies. Their complex structures make it very hard to fully understand their behavior.

$$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \rho \bar{f}_i + \frac{\partial}{\partial x_j} \left[-\bar{p}\delta_{ij} + \mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u_i' u_j'} \right] \tag{2.3}$$

$$u(\boldsymbol{x},t) = \bar{u}(\boldsymbol{x}) + u'(\boldsymbol{x},t)\,, \text{ where } \boldsymbol{x} = (x,y,z) \tag{2.4}$$

$$\overline{u'} = 0 \tag{2.5}$$

The laminar flow becomes unstable to small disturbances when the Re (Reynolds number) is greater than the critical value of critical Reynolds number. So the number serves as an assessment criterion for flows (fig. 2.4).

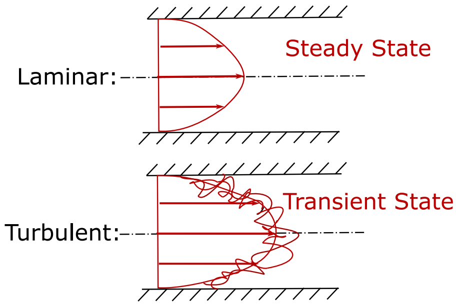

Figure 2.4: A channel flow

It is usually not necessary to consider the details of each individual vortexes and the changes of quantities in the flow via using the numerical flow simulation. In many cases, it is enough to analyze their effect on the total flow. Therefore, the velocity variables are divided into averaged velocity and fluctuating velocity (eq:2.4) (fig. 2.5). The Reynolds-averaged Navier-Stokes equations (RANS equations) (eq:2.3) are obtained by inserting them into basic equations with the help of two main turbulence models. [38]

In simple terms, we accept the time average of the fluctuating velocity component is zero (eq:2.5). When we average the equation terms, this simplifies the equations.

The basis of the RANS equations is the most exclusive method for industrial problems, because of its simplicity. The quality of the results is not that good as the results of the LES method but most of the cases they are good enough.

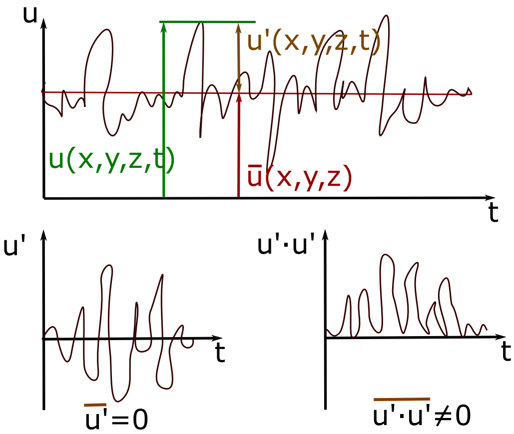

Figure 2.5: Average velocity and fluctuating velocity

2.2.2 LES (Large Eddy Simulation)

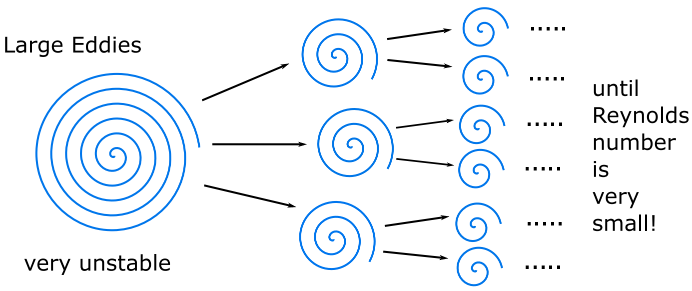

Figure 2.6: Large eddies into small eddies

One of the most exact solutions for the turbulence flow is the Direct numerical simulation (DNS) method in CFD. The eddies are not stable at all and the energy, which the large eddies contain, is releasing by separating them into small pieces. That is why the large eddies divide themselves into smaller eddies until the Reynolds number is small enough (fig.2.6). Because of this continuous change, the DNS method requires very fine meshing in Finite Element Method (FEM) and very small time steps to be able to simulate the actual flow.

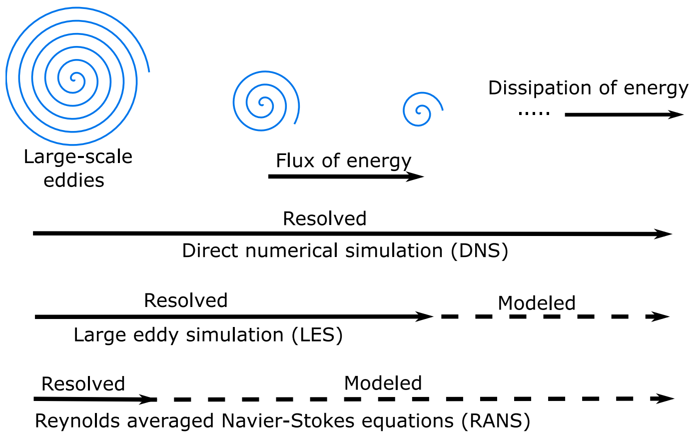

Figure 2.7: DNS vs LES vs RANS - Modeled

The Large Eddy Simulation or LES is a mixture of the RANS and DNS methods. The LES method solves only the large Eddy (vortex) structures and describes the small ones with a model. Involving the large eddy in simulation makes the computing effort very high, but the quality of results is much higher than RANS and close to the DNS method.

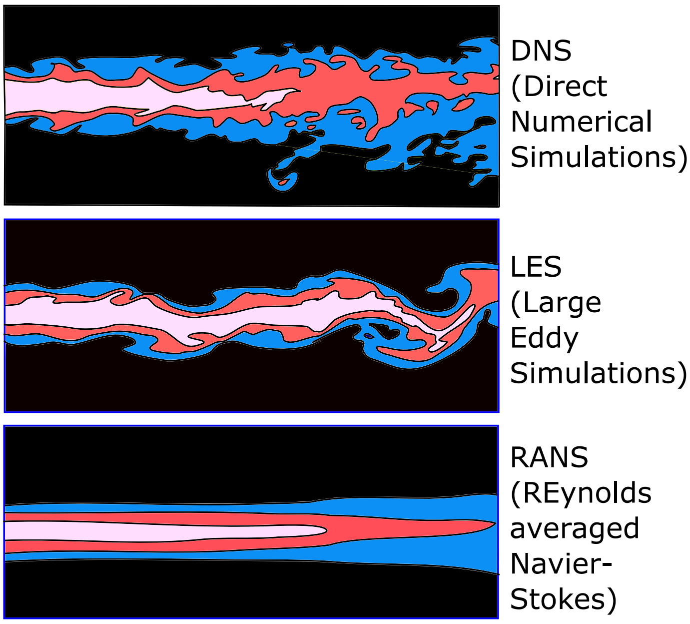

Figure 2.8: DNS vs LES vs RANS - Visual

DNS methods are extremely complex and can only be used for very simple geometries. It is not practical to use for engineering analysis. In fig.2.7 we see the difference between those three methods, DNS, LES, RANS. With the help of fig.2.8 we can understand the difference between the visual results (outputs) of these three different methods. The engineers can simulate the flow character very close to the real-world with the DNS method. But we engineers are not after the real result. We are after the useful proximate analysis. That is why the most commonly used one of those methods is the RANS method. The software calculates the flow up to a certain point and then use the established models, which is mentioned in the last subsection.

2.3 Prototype Shipbuilding

In a ship model basin, the tests and experiments with a ship model are performed in a basin (pool), which is filled with a liquid (often water). The basins are basically large pools with mechanisms, which can generate currents and/or waves in a targeted manner. In these pools, the ship models are tested with a different level of currents and/or waves to measure their water resistance.

At the Naval Surface Warfare Center in the Maryland suburbs of Washington, D.C. they have a football-field size pool, which can recreate eight ocean conditions (from flat calm to typhoonlike) with its 216 electronically controlled wave boards. It is one of the most advanced scientific wave testing basins of its size in the world.[39]

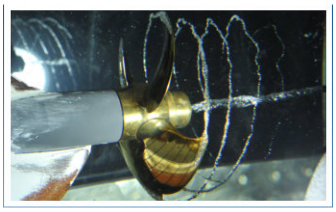

Figure 2.9: Cavitation tunnel in Vienna Model Basin [40]

The purpose of ship model testing in a model basin is getting data with a reduced scale model based on similitude theory in order to estimate the hull form and form parameters for the boat design with actual dimensions. These methods are used to get information about the stability, seakeeping, and maneuvering of the ship. Also, propeller testing is necessary. In the cavitation tunnel (fig.2.9), propulsion analysis is performed to measure the quantities to find a better way to avoid cavitation. Cavitation is a very interesting fact, how the steam-filled cavities (steam balls) (fig.2.9)are formed and are popping because of the rapid changes of pressure. This occurrence damages the steel surface of the propeller. Intact Stability, Buoyancy and Damaged Stability are some other components, which are also being analyzed.

Resistance and propulsion tests are the most performed tests in the ship model basin. These are used to examine the effect of the hull design on water resistance and to define the necessary motor power to achieve the required speed. Also, after-flow measurement is made to analyze the flow field behind the ship to know the flow velocity at which the propeller will work.

These ship model basins are also used to analyze the conditions (sea state, wind speed, etc.), under which the ship is operating, and the response of the ship to these conditions for programming the CFD software programs. These conditions and responses become functions and simulations in the CFD software programs. That is why we can say that the CFD methods are the virtual ship model basins in our computers. These programs are getting better results for the fluid dynamics problems every day and it makes them more attractive for the engineers with their low costs. Nevertheless, the ship model basins are still required for a big project such as a very large merchant ship (cargo ship) project or navy projects.[41]

2.3.1 Model-Ship Extrapolation

The ship's models for the resistance test, which are used in a model basin, are much smaller than the actual size of the ship. Because the engineers are using the models to predict the ship power, the quantities of the resistance test results have to be scaled or extrapolated from model size to real size of the ship to get the correct results.

$$\mathrm{Fr} = \frac{u}{\sqrt{gL}} \tag{2.6}$$

$$\mathrm{Re} = \frac{\rho u L}{\mu} = \frac{uD}{\nu} \tag{2.7}$$

Froude number (2.6) and Reynolds number (2.7) (u-characteristic flow velocity, g-characteristic external field, L-characteristic length, ρ-density of the fluid, μ-dynamic viscosity, and ν-kinematic viscosity) are the two most known numbers to calculate the water-resistance quantities in model testing. These equations are used to scale up the obtained result of the test to real conditions. But it is impossible to satisfy simultaneously the equality of Reynolds and Froude numbers. That is why the test results should be extrapolated from model size to the real size of the ship.

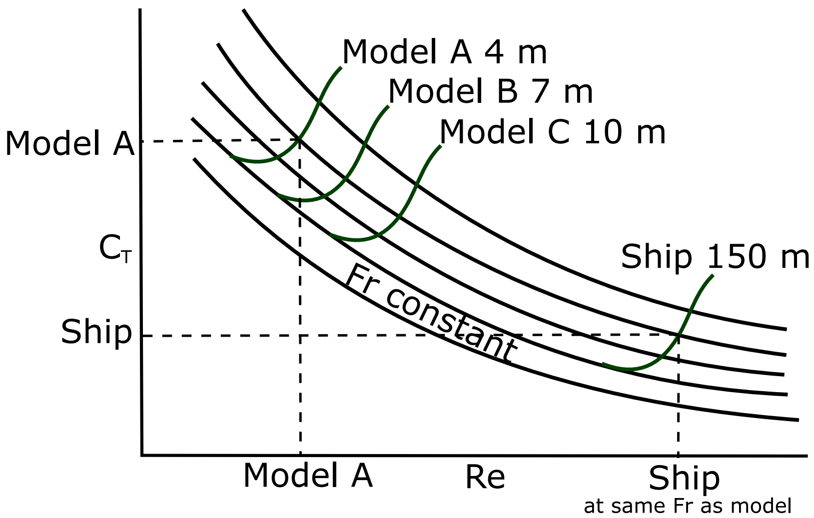

Figure 2.10: Extrapolation - Geometric Similar (Geosim)

Several resistance tests should be run for a range of different sized models of the same main hull geometric form. For example, as seen the fig.2.10 the first test is done with the Model A, which is 4 m long and the next test is done with the Model B and the next one with Model C and it can go like this until we have a clear diagram to calculate the resistance coefficient for the real size. After several tests have been run we can extrapolate the resistance coefficient from Reynolds number of the model to the Reynolds number of the ship. [42] [43]

2.3.2 Vienna Model Basin LTD

The Vienna Shipbuilding research Institute (SVA) and Vienna Model Basin Ltd is a non-university Austrian research institute, which is one of the best and oldest in Europa and it belongs to Prof. Gerhard Strasser. He is still teaching under the roof of our university. In fig. 2.11 we see the basin (180-meter long pool) and on it, there is a bridge, which can move along the pool.

Figure 2.11: The pool in Vienna Model Basin [40]

In fig. 2.12 we see the model, which is connected with the bridge and ready for the test. There is just the main hull as a testing object. The upper portion of the ship is not necessary for measuring the quantities of water resistance. The effect of upper portion weight can be achieved by putting additional weights on the main hull. This method allows us to simulate different conditions by changing the position of the additional weights on the main hull. The bridge moves with a certain speed and it pushes the model with it to create a dynamic simulation in order to analyze the hull design efficiency. The most important factors are speed and fuel consumption to determine efficiency.

In Vienna Model Basin Ltd, there is just one body to generate waves in order to simulate the wave effect on models. It is an old way to do it. New ones have several parts and the parts can move independently from each other so they can generate different kinds of waves as well.[40]

Figure 2.12: Testing in Vienna Model Basin [40]

Chapter 3

Analysis of the Volitan Yacht Design

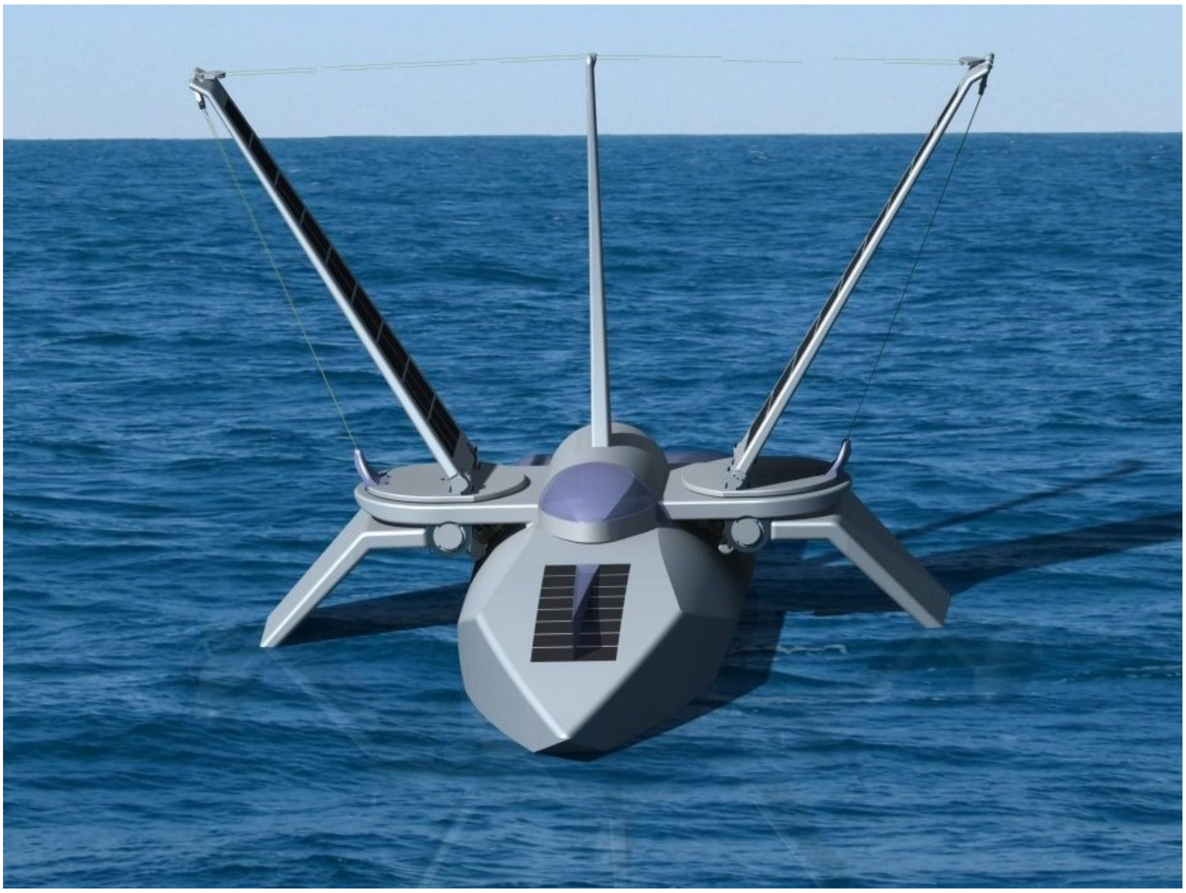

Figure 3.1: Volitan Yacht Design

3.1 The Form of the Volitan Design; Advantages and Disadvantages

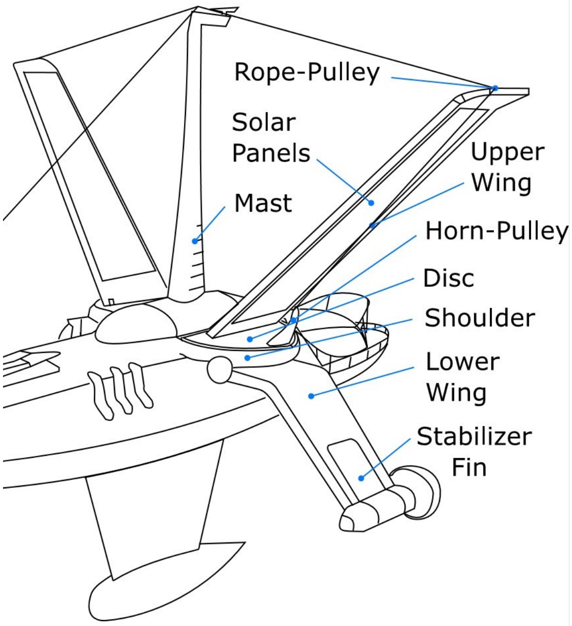

Figure 3.2: The parts of Volitan Yacht Design

The Volitan is a luxury 32 meters long concept sailing yacht with many features. These are extraordinary futuristic parts such as the two solid sails on the side of the boat. In the fig.3.2 we see the parts of Volitan and their names, which will be mentioned in the following sections/subsections. The shoulder is a ledge, which is attached directly to the main hull and has no degree of freedom (DOF). The lower wing is fastened on the shoulder with two plain bearings and two hydraulic cylinders. It has one DOF, which allows it to lift up and close down. On the lower wing, there is the stabilizer fin, which is located at the end of the wing and around the electric motor capsule. It has the same DOF as the lower wing. It allows the fin to turn around the axis. On the upper side of the shoulder, there is the disc, which holds the upper wing. The Disc is fastened with the shoulder via thrust spherical plain bearings. It has one DOF on the vertical axis. This allows the disc to turn in the vertical axis. Because of the disc, the upper wing is getting the first DOF in the same direction, because they are fastened together with 6 cylindrical roller bearings. These bearings give another DOF to the upper wing to shift and tilt according to the wind condition. This movement is done by pulling the sail towards the rope pulley. This rope pulley is connected with the mast and with the Horn-Pulley by rope. And the horn-pulley is fastened with screws to the disc. The horn-pulley is a rope pulley, which looks like a horn. That is why it is called horn-pulley. Also, the disc is a name, which is given in this study.

Afterward, these mechanisms will be discussed in further detail with the designs in 2D and 3D, which are constructed in CATIA. The futuristic parts are also analyzed in FEM via ANSYS and CATIA to find out the best possible way to achieve the features, it promises. The Volitan Yacht does not exist. It is just a design because the yacht design is not yet manufactured.

3.1.1 Second Momentum of Area, Moment of Inertia

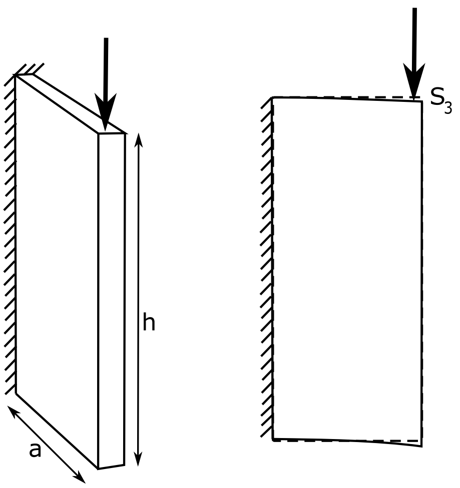

Figure 3.3: Area moment of inertia - Example 2

The upper wings are fastened to the shoulder with bearings at the bottom. And they are connected to the mast and to the horn-pulley by rope at their tip points with rope pulleys. The area moment of inertia of the upper wing about the axis, which is in the bending direction, is the smallest one related to the other axes. In this condition, whichever is fixing a long and thin object at its endpoints has the risk of mechanical resonance. It may cause a disturbing vibration on the boat or the destruction of the bodies due to excessive vibration if the structure is improperly constructed. Normally monohull or catamaran sailing yachts have the sails at the center-line of the boat and the sails are connected and fastened to the mast along all their length. In fig.3.3 a similar structure of the traditional sail condition is shown with a simple example. As we learned, in this case, the area moment of inertia is much bigger against bending than the structure, which the Volitan design has. This gives the structure a very good damping effect along its length for the whole of the sail. This aspect shows us the disadvantage of the fastening design for the upper wings. On the other hand, the X profile has an advantage over the category of mass moment of inertia.[44]

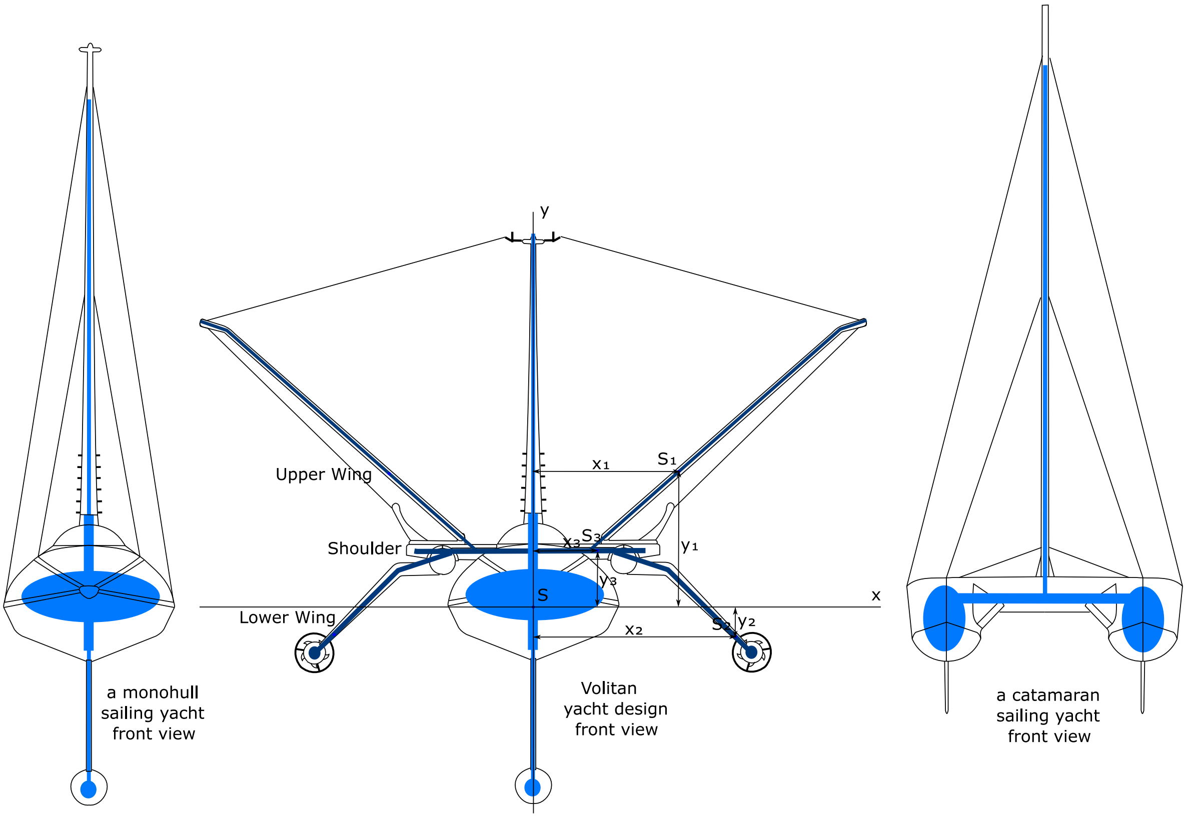

Figure 3.4: Monohull vs Volitan vs Catamaran

The area moment of inertia should not be confused with the mass moment of inertia, which characterizes the inertia of a rotating body by angular acceleration. It goes up with the increasing distance from aches of rotation. If we accept that the center of gravity is within the rotation axis (fig.3.4). The distances x_1,y_1; x_2,y_2; x_3,y_3 of the additional bodies, which are the upper wing, the shoulder, and the lower wing in Volitan, increase the mass moment of inertia. This greater inertia would provide a better sailing comfort, because the greater inertia is, the more external moment, which is obtained from wind and sea waves, is necessary to roll a boat. In fig.3.4 we can compare the Volitan design to a monohull sailing yacht and a catamaran sailing yacht. The difference in the mass moment of inertia about the axial axis between these three designs is obvious with the help of colored lines and figures. Sailors would know that sailing comfort with a catamaran is much better than with a monohull but in case of rough sea, monohull is a better choice than a catamaran, because catamaran has two hulls with a wide distance between them. The waves are reacting with one hull at a different time than they are with the other hull. This motion swings the boat worse than with the monohull. We would not have the problem with Volitan design, because these lower wings do not have volumes as much as a hull. That is why the buoyancy on the lower wings is not that strong to swing the yacht.[45]

3.1.2 Mechanical Aspects on Lower Wings

The main function of the lower wings is holding the 200 HP electric motors, which is one ton. The location of the motors allows the boat to turn around with a minimal turn radius. Because the lower wings can be lifted up and closed down, the location of the motors can be adjusted to achieve better handling and maneuvering of the boat. But it comes at a high cost. Holding an one ton electric motor is a challenge. Especially, the shape of the lower wing is not the best design for this purpose. This aspect will be discussed in the FEM analysis section in detail.

The lower wing has an additional part, which is the stabilizer fin. It works as an extra keel to stabilize the boat more. If the boat sailing forward, these would work well. The downside of the stabilizer fins is that they can create additional water resistance - when the fins are opened, the surface of the fins would increase water resistance acting on the boat and also opened fins leave a square hole on the lower wings, which is the nest of the fin, and that creates turbulent flow by the lower wing.

The stabilizer fins can be designed as hydrofoils (fig.3.5) to lift the hull out of the water by using dynamic buoyancy. It can reduce the water resistance when the less surface of the hull touches the water. There are lots of good examples for this approach such as Hydrotere (fig.1.24) and Sail Rocket (fig.1.23), which show that this is a possible feature. Ordinarily, the hydrofoils are connected directly to the main hull with screw plate mounts or they have the mobility of only one degree of translational movement, which makes it possible to lift or lower the foils. The connection between the foil and hull can be really strong against momentums, if there is no degree of freedom in the rotation axis.

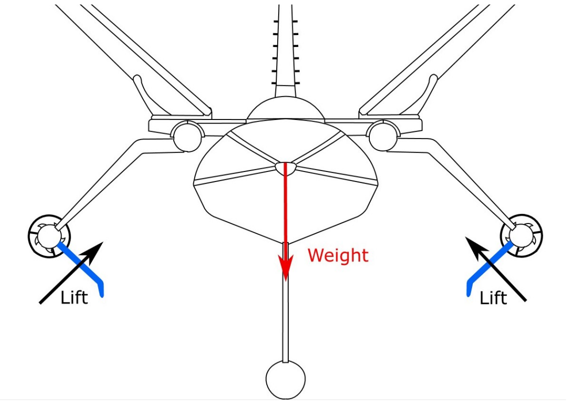

Figure 3.5: Volitan-Hydrofoil

On the other hand, in Volitan design the foils are connected to the lower wings and they have rotational motion around the connecting point. Also, the lower wings have the same ability around the connecting point with the main hull. These turning points must be designed very carefully when we want to lift the whole yacht only with the foil lifting surface.

The other problem for this approach is the hull length. The Volitan design is 32 meters long. There is no example for a 32 meters long sailing yacht with hydrofoils. It does not mean that it is impossible but some time is needed to have the technology to build something like this.

3.1.3 Mechanical Aspects on Upper Wings

In general, the sails are connected to the mast, consequently to the main hull. In this way, the sails can be fixed at the center-line of the boat to the mast along all their length. And it gives them great stability against wind power. It is very logical to fasten the sails/wings to the mast when there is already the mast option, which is very easy to build at the center of the boat.

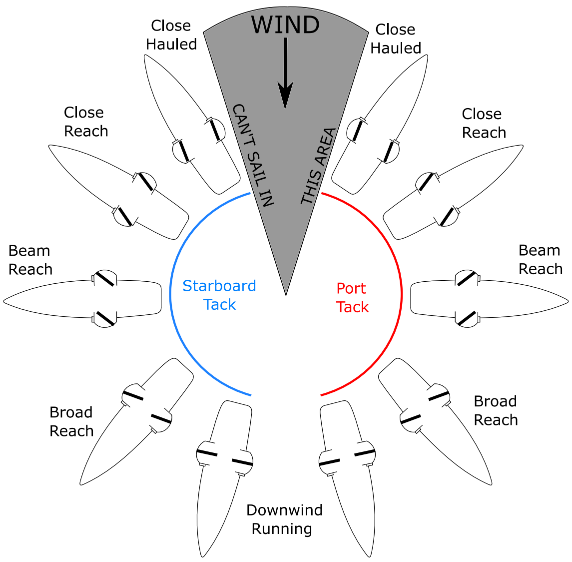

Figure 3.6: Points of sailing

The double wing design is pretty rare in yachts' design. One of the examples of this concept is called Hobie TriFoiler[46]. It has a double big size windsurfing rig on the right and left side of the small 145 kg catamaran with hydrofoils. The reason why the kind of boats are not common in the world is their smaller ratio of the efficiency and the cost of manufacturing the boat than regular designs. The structure is much more complicated when the sails (wings) are separated from each other and they are fixed on the right and left side of the yacht with an extension.

In the Volitan design, this feature serves for the solar system. As we learned in the subsec.1.1.1, the angle of incidence on the solar panel affects the power output. The mobility of these upper wings allows the solar panels on them to get the best angle to convert sunlight into electricity.

The shape of the wings is another important aspect to have a good efficiency onboard. In fig.3.7, we see some airfoil profiles as well the position of them according to the true wind direction and the direction of sail. The first one is the most famous one, which is called the modern asymmetrical airfoil. They are not suitable for sailing unless the point of sail is always on the close-hauled or -reach, in port tack. The second one is the high lift wingsail airfoil, which is used in America's Cup and has really good results. It is adjustable for any points of sail. As well as the third one, the typical sailboat airfoil is adjustable due to its soft structure. In America's Cup, they used the wingsails to achieve a taller sail without experiencing excessive loads. And the control of the sail is much easier than soft sail. But the sailboat airfoil is still one of the best airfoil types for sailing. The Volitan airfoil, which is shown in the introduction pictures of the design, is not a useful airfoil but it can be easily modified in order to have better lifting and it can be a symmetrical airfoil. This type of airfoil started to be used and got good results. My choice would be the high lift wingsail airfoil or the symmetrical airfoil for the Volitan design.

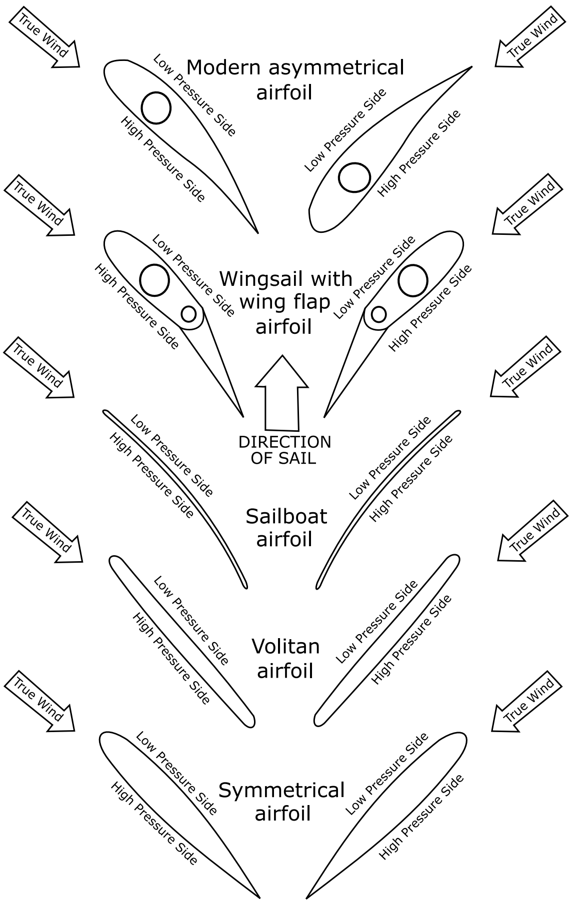

Figure 3.7: Airfoil designs

3.2 ANSYS Topology Optimization

Using the function of topology optimization the engineers and designers are able to reduce the weight of the components of the product. In using this software, it is wise to have a simple body such as a block for the first calculation as the software is higher performing when calculating simpler parts of the overall design. After the first topology optimization, we then can see the best way to reduce the weight and redesign our product.

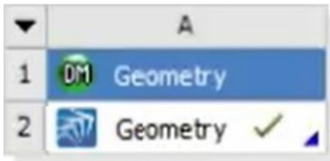

Figure 3.8: ANSYS-Geomerty

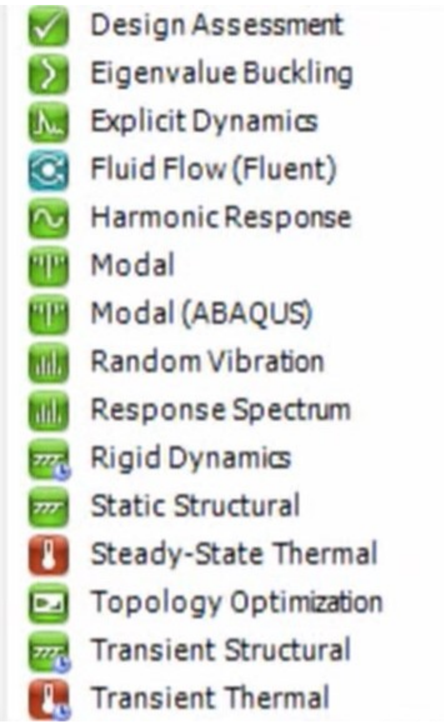

Figure 3.9: ANSYS-Sections

In this design, the parts were created in CATIA V5 and then stored the 3D design data in STP files in order to exchange the product model from CATIA V5 to ANSYS. The Volitan parts could have also been designed in the Space Claim software and directly imported them to ANSYS. It is the designers choice on which system to use, and for this purpose, CATIA was used.

After exchanging the model to Space Claim the geometry was transferred (fig.3.10). From there, a mesh was generated. To have a better, more detailed, result, the size function can be adjusted to have smaller elements for meshing. The size of specific elements can be changed to get finer mesh, especially around the area where the boundary condition is applied via using the "proximity and curvature" option in the size function. Once the boundary conditions and the forces for the part were set, the equivalent stress solution was added. After running the solution, the topology optimization was tracked on over the solution cell. Space Claim will automatically exchange the information from the static structural analysis just completed, onto the topology optimization analysis. (fig.3.9) For this design aspect, the mass was optimized, but any of the followings could have been selected to optimize: volume, displacement, global stress, local stress, and reaction force. The optimization for mass will remove all sections which do not carry any load or which carry much less load than the main section. If the parts were meshed in very fine detail, in order to create a better solution, the process will take too long for topology optimization, and also a lot of storage space is needed on a computer which is not ideal. After receiving results, they are transferred to the Design Validation System which transfers the result to a new static structural system. After updating the sections, it brings them back to Space Claim. Now, the two systems can be seen together and the object can be cut to see the cross-sections, which were the target for examination in this study. Studying the cross-sections provides an idea about how parts should be designed.

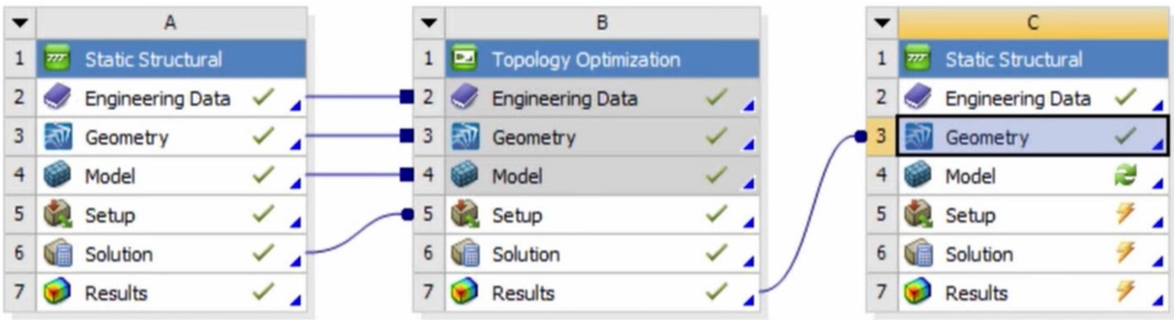

Figure 3.10: ANSYS-Launchs

3.2.1 Topology Optimization of Lower Wings

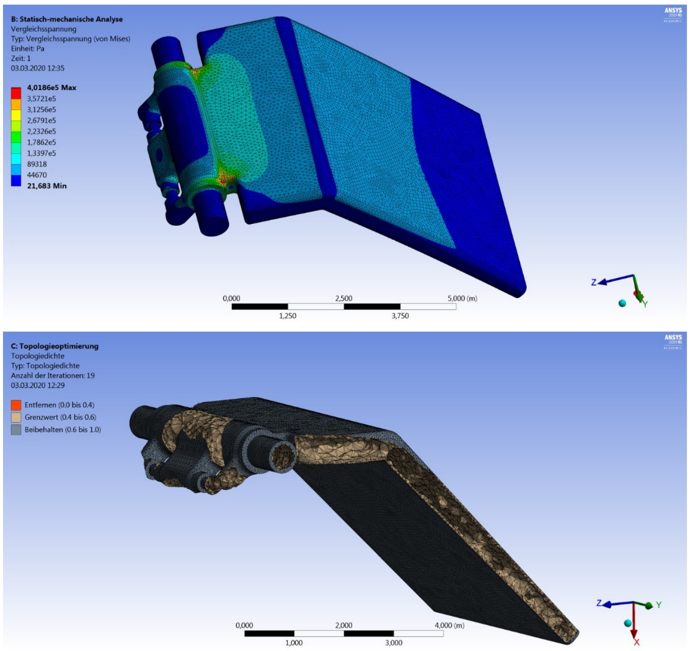

Figure 3.11: ANSYS-Topology optimization-Lower wing

The boundary conditions are entered for the two plain bearings and the two hydraulic cylinders to fix the upper wing. The water-resistance forces and the load of the electric motor are added to simulate the condition for the parts. The fixed support is inserted and makes the tangential component of this boundary condition free. It then allows the shafts to rotate in the joints.

In fig.3.11 we see the result of the optimization. It looks like a spider web, and it is impossible to manufacture some products exactly in this shape without a very large 3-D printer. The part is around 9 meters long and it makes the manufacturing process harder. The sandwich-structured composite with honeycomb structures would be the nearest structure to the result of the optimization, which can be manufactured without the need of 3D-Printers. They can be manufactured from fiberglass or carbon fiber and also from a metal, usually aluminum.

In fig.3.12 we see the cross-sections, which show us the inner structure after the optimization. These show us some idea of how the lower wing should be designed. In the first, left, picture, we see the shaft for the plain bearings and the handles for hydraulic cylinders. These journals for the plain bearing can be hollow shafts. In the second, middle, picture we see a very dense structure, which is the midpoint of the lower wing. It means that this section should be more strongly supported than in the next, less dense, section. Of interest, there are also two short lines of density moving down the middle of the structure, towards the end of the surface. In the last section, shown on the right, there are again those two continued lines of density, this time along the bottom section of the lower wing. Two main columns can fill the need for these two denser lines, showing the structure from the beginning of the lower wing until the endpoint. The inner structure of this part of the lower wing will be discussed in the next section in detail.

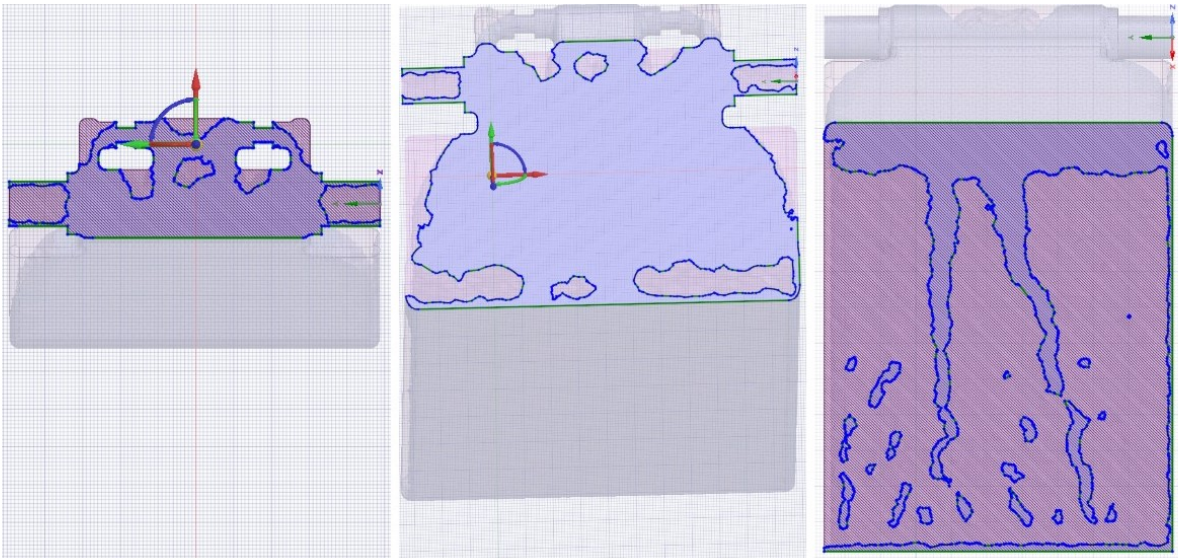

Figure 3.12: ANSYS-Topology optimization-Lower wing's cross-sections

3.2.2 Topology Optimization of Upper Wings

The topology optimization for the upper wing did not give as much information as the optimization for the lower wing. There we see the disbursement of the structure in the cross-sections of these figures 3.13. This optimization means the structure is under almost equal pressure on all areas. Because the pressure is almost equal in all areas, meaning there is no area which has a particularly high-stress concentration point, carbon fiber, fiberglass, or a hybrid of carbon fiber and fiberglass, are some of the best choices to achieve a low weight and high stiffness wing. In this condition designing a structure similar to the wind turbine blade is appropriate for this exploratory design as we learned in the subsec. 1.2.2.

There is a high material density for the plain bearing bush around the seat, therefore to design a strong structure around these seats would be a good idea. The frame structure should be made of a little bit stronger material than carbon fiber, in order to hold the entire structure straight. These aspects will be discussed in the next section in detail.

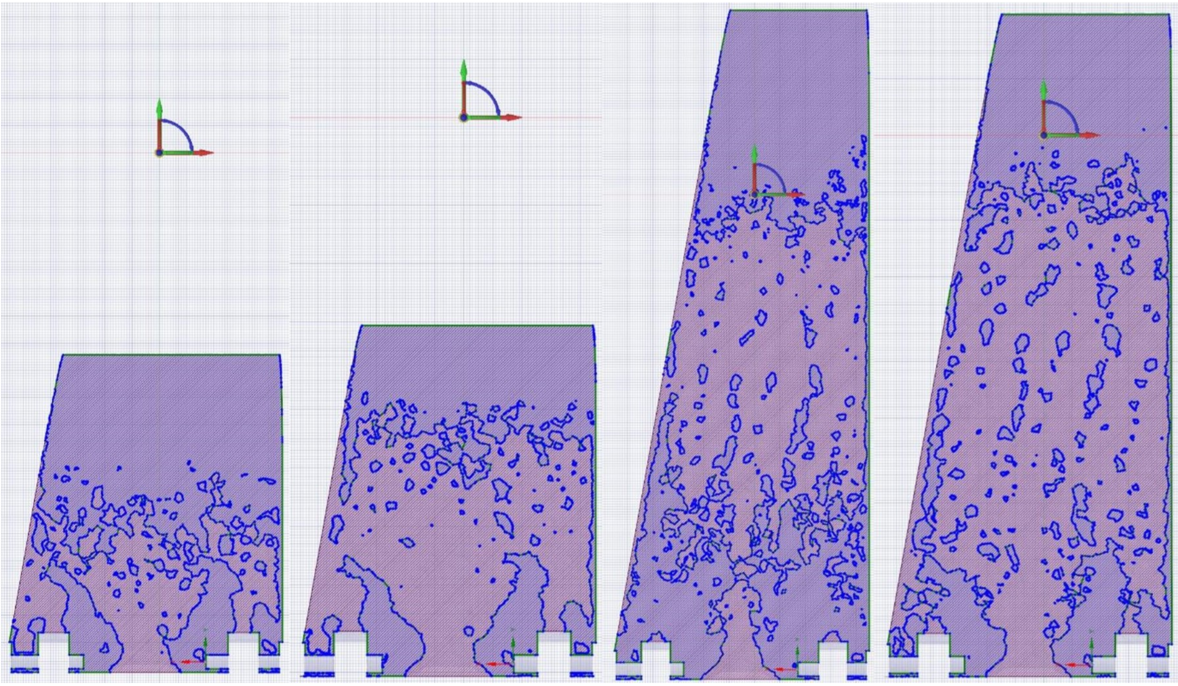

Figure 3.13: ANSYS-Topology optimization-Upper wing's cross-sections

3.3 CATIA V5 Analysis of the Design

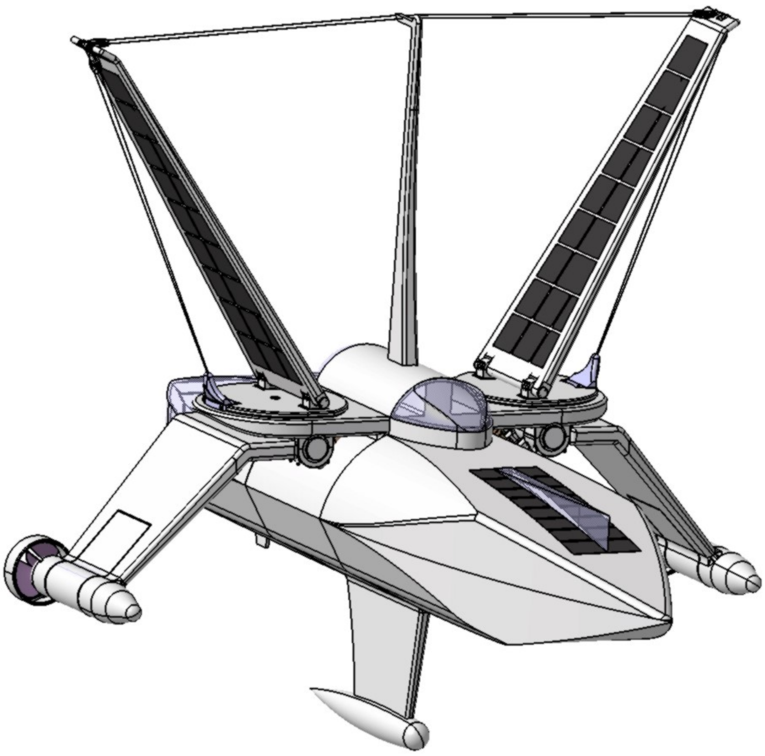

Figure 3.14: Volitan Yacht Design

In fig.3.14 we see the product, which is designed in CATIA V5 to analyze the Volitan yacht design. It is an assembly design with 17 sub-assemblies as follows; two discs products, two wing products, two lower wing products, four hydraulic cylinder products, two shoulder plain bearing products, four rope parts, and the main hull with the shoulders.

The hull design of the product does not look like the hull design from the actual Volitan design since the parts, that will be examined, are upper wing, disc, shoulder, and lower wing. However, a simple hull design is created to complete the full picture of the boat design.

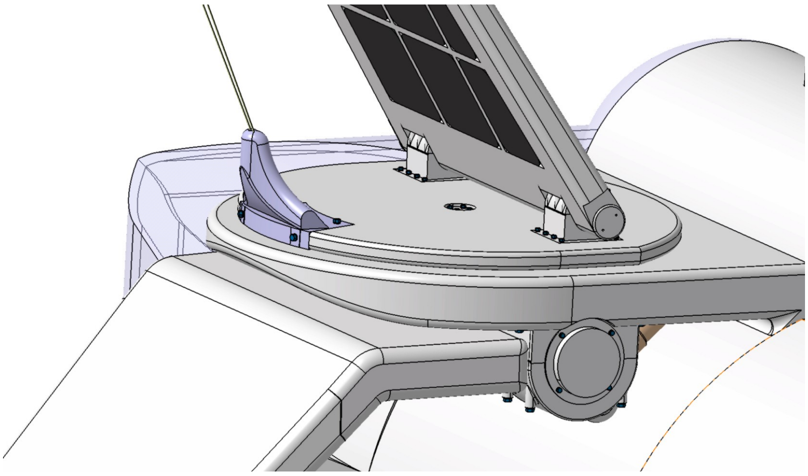

Figure 3.15: Volitan Yacht Design - Right shoulder

In the fig.3.15 we see the right shoulder part of the design, which is the ledge to hold the upper wing and lower wing. Because it is attached directly to the main hull, it has a strong connection with the yacht. It gives the shoulder enough strength to carry all the extra load of these futuristic extensions. The lower wing is fastened on the shoulder with two plain bearings. We can see the housing of the plain bearing in the picture in the right.

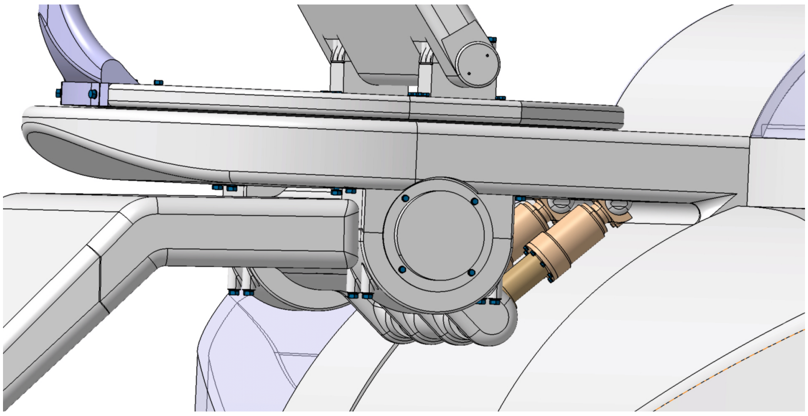

Figure 3.16: Volitan Yacht Design - Left shoulder

The two double-acting hydraulic cylinders (colored gold in fig.3.16) provide the movement of the lower wing. The base of the hydraulic cylinders are attached to the shoulder and the other side of them to the lever arm of the lower wing. They can move the lower wing up and down with the help of the lever arm. This lever arm is an extension at the connection point of the lower wing to the shoulder.

On the upper side of the shoulder, there is the upper wing, which can swivel left and right and tilt forward and backward. There is also the disc part to achieve the swiveling left and right movement of the upper wing, which also holds the upper wing and connects it with the shoulder part. The thrust spherical plain bearings, which fasten the disc with the shoulder, allow the disc and the upper wing to turn in the vertical axis. The 6 cylindrical roller bearings, which fasten the disc and upper wing together with two housings, allow the movement of the tilting forward and backward.

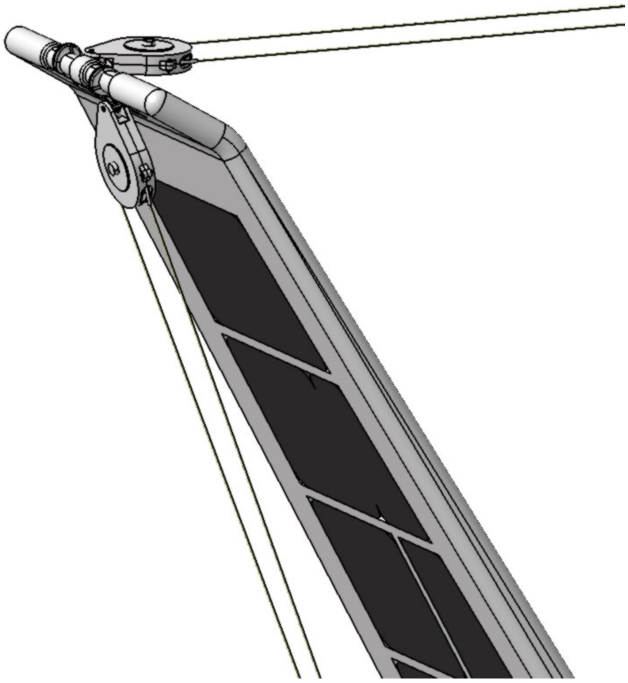

Figure 3.17: Volitan Yacht Design - Rope pulley

The Rope pulley provides the movement of tilting forward and backward for the upper wing. They are also holding the upper wing in the desired position. There are four rope pulleys for each upper wing. The first one is fixed at the tip of the disc (fig.3.15), which is called horn-pulley because of its shape. The second and third ones are located at the tip of the upper wing (fig.3.17), one of them connects the tip of the upper wing with the horn-pulley. The other one connects the upper wing with the fourth rope pulley, which is at the top of the mast. As mentioned previously, connecting the upper wing at its tip point with the rope pulleys, has the risk of mechanical resonance. At the same time, the area moment of inertia has one of the lowest values about the bending axis. (Subsec.3.1.1)

In this section, we will also discuss the inner structure of the upper wing and lower wing. Aluminum is chosen to use as framing material because of their low density, good mechanical properties, and they are suitable for various process methods. The material aluminum belongs to the group of light metals. Aluminum is three times lighter than steel but also has lower mechanical properties. If we look at the ratio of strength to weight, aluminum is the winner. It has a tensile strength of 60 to 95 N/mm^2 (MPa) and a 0.2% proof stress of at least 20 N/mm^2. The modulus of elasticity of aluminum is 70000 N/mm^2, which is lower than the modulus of elasticity of steel (210000 N/mm^2). But aluminum alloys to have much better tensile strength and yield strength. They can achieve a tensile strength of up to 700 N/mm^2.

Carbon fiber is chosen to use as the covering/skinning material because of their very low density (perfect for lightweight constructions), high strength, and you can cover anything with a thin layer carbon fiber. It means, that it is very easy to give shape to carbon fiber by covering/skinning. (Subsec.1.2.2) Because of these aspects, carbon fiber is the most commonly used material in aircraft, aerospace, and wind energy industries.

3.3.1 Joining the Upper Wing to the Disc

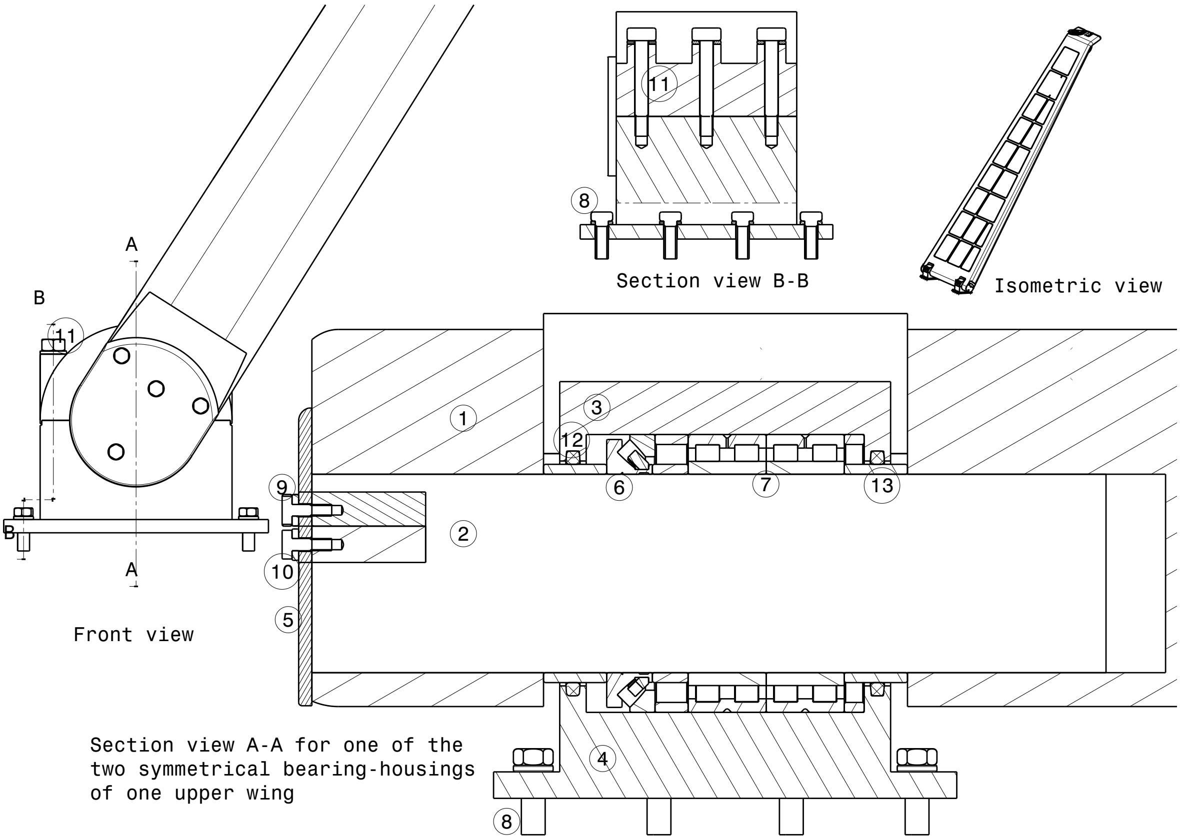

Figure 3.18: Upper wing - Rolling Bearings

1. *upper wing*, 2. *shaft*, 3. *upper housing*, 4. *lower housing*, 5. *Cover*, 6. *Spherical roller thrust bearing* (29260), 7. *two SKF double row cylindrical roller bearing* (*NNU* 4960 *B*/ *SPW*33), 8. *Screw* 130 *M*36 (8 *pieces for one housing*), 9. *Screw* 75 *M*20 (*two pieces for one cover*, 10. *Screw* 75 *M*20 (*two pieces for one cover*), 11. *screw* 300 *M*36 (6 *pieces for one housing*), 12. *mechanical water shaft seal ring*, 13. *spacer sleeve* (5 *pieces for one housing*)

The upper wing(1) is 14,4 m long and has 60 m^2 surface area on each side. If we calculate the wind pressure in bad weather conditions (velocity of the wind is 100 kph), it is around 245 Pa (eq:3.5). And if the wind hits the wing directly at the 90° angle, the wind force would be 14700 Newton (14.7 kN). In order for the upper wind to be able to embrance that amount of force,it needs to have very strong bearings at the connection points. In general, the plain bearing can be considered to be a stronger bearing option than the rolling bearing, because they have no rolling elements (these rolling elements are used to create the relative velocity between the outer ring and inner ring of the bearing, which are in form of balls or rollers). On the other hand, the rolling bearing has significantly lower resistance between moving elements, since they rest on a small area of the rolling elements. It means the plain bearing has a higher friction loss by start off than the rolling bearings.

$$C_e = 0.80 \text{ exposure factor, combined heiht and gust factor (0.6-1.2)} \tag{3.1}$$

$$C_d = 0.65 \text{ drag factor (shape) (0.09-1.15)} \tag{3.2}$$

$$\rho = 1.225 kg/m^3 \text{ density of air } v = 100 kph \text{ wind speed} \tag{3.3}$$

$$Q_s = 1/2 * \rho * v^2 \tag{3.4}$$

$$P = C_e * C_d * Q_s = 245.75 Pa \tag{3.5}$$

The upper wing will be often moved to catch the wind or to get the best angle of incidence on the solar panels. In this condition, the bearings will work at low speeds, where speeds change frequently and at high loads with little friction. The rolling bearing is the best choice for the upper wing joints. Having low friction by the start off improves the smoothness of the movement, therefore the parts can move more easily. In our case, it is very important that the upper wing moves easily because it would make the situation more complicated if we put more force at the top of the upper wing with rope pulley to move it.

Another advantage over the plain bearings is that the rolling bearings manufacturers such as the SKF have a calculation tool to calculate the bearing rating life (see weblink [47]). We can enter the information of the work conditions for the joints in the tool and choose the bearing online via calculation tool, which suits the best for our condition. The calculation of the bearing rating life guaranteed the functional safety of the machine.

The roller bearings can be subjected to greater loads than ball bearings. And if there is a slow relative movement between the upper and lower ring of the bearings, the advantage of the ball bearings is not significant anymore. The roller bearings are also a better choice for large shaft diameters. That is why the roller bearings are selected for the application.

If we want to look at the construction of the bearings, the DOF is a relevant aspect depending on in which direction the shaft should be able to move or rotate and in which direction it should be blocked. In this aspect, we can separate the bearing in three categories as radial bearings, axial(thrust) bearings, and linear-motion bearings. Two double row cylindrical roller bearings (NNU 4960 B/SPW33 SKF(7)) and one spherical roller thrust bearing (29260 SKF(6)) are selected. In simple words, each upper wing is fastened with total 4 radial double row cylindrical roller bearing to achieve high strength in the joints and 2 spherical roller thrust bearing to block the movement of the shaft in the axial direction. (fig.3.18)

These bearings are in the bearing housing(3,4) and the housing is fastened with 8 screws(8) to the disc. The housing has two parts as the upper housing and the lower housing and they are fastened with 6 screws(6) to each other. The separation of the housing into two parts makes the montage possible. The bearing housing blocks the shaft on the radial axes and the cover(5) blocks the shaft on the axial axis. The cover(5) is fastened to the shaft with 2 screws(9) and at the same to the upper wing with 2 screws(10). This connection locks the shaft into the upper wing. In the isometric view in fig.3.18 we see one upper wing with two bearing housing. This fixing on both side increases the stability of the upper wings.

3.3.2 Joining the Disc to Should

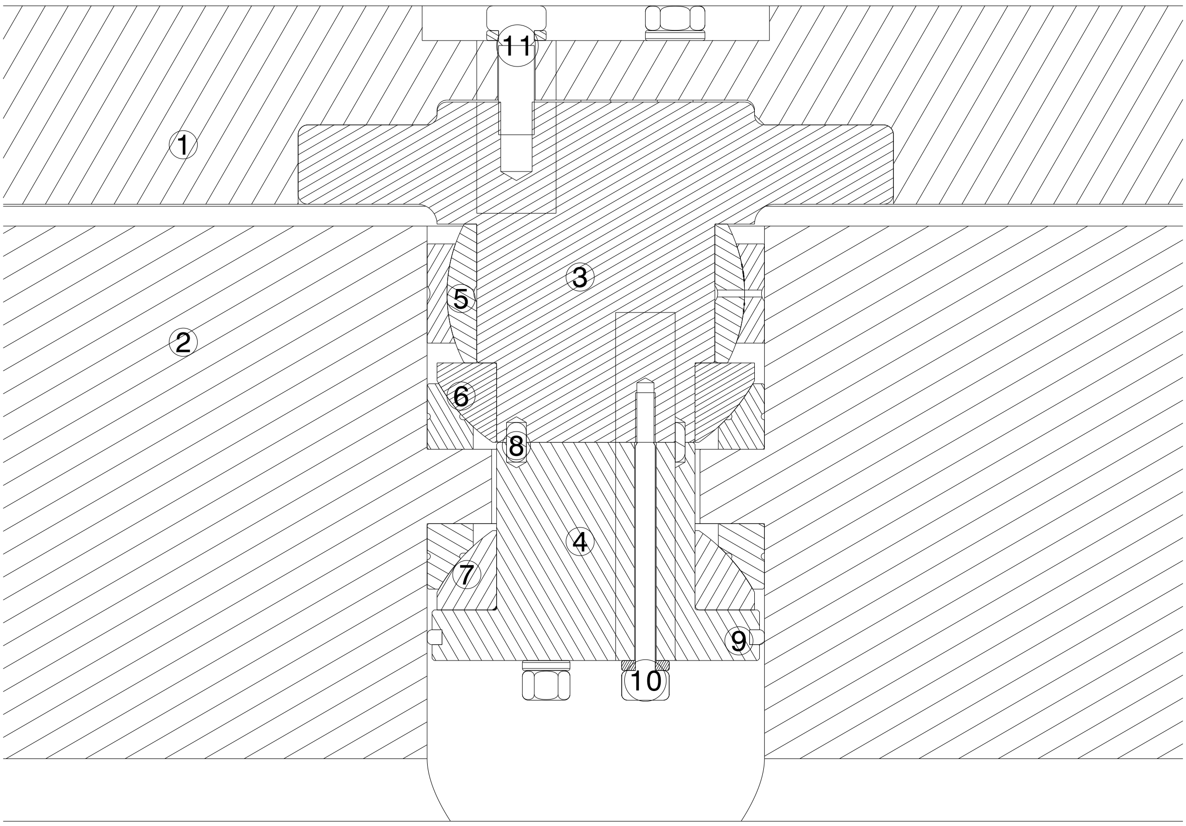

Figure 3.19: Disc - Plain Bearings

1. *Disc*, 2. *Shoulder*, 3. *upper T−shaft*, 4. *lower T−shaft*, 5. *radial spherical plain bearing* (*GE* 240 *ESL* 2*LS SKF*), 6. *Upper thrust plainbearing* (*GB*/*T* 9162 2001 *GX*200*S*), 7. *Lower thrust plain bearing*, 8. *centering pin* (2 *pieces*), 9. *mechanical water shaft seal ring*,10. *Screw* 310 *M*20 (4 *pieces for one disc*), 11. *Screw* 130 *M*36 (4 *pieces for one disc*)

The disc(1) is the part look like a plate, which carries the upper wing and is connected to the shoulder(2). We have just finished the subsection about the joining the upper wing to the disc with the roller bearing housing. The disc has one degree of freedom on the vertical axis. This allows the upper wing to turn with the disc in the vertical axis. Plain bearings are selected for this application because the starting torque is not a problem this time. Unlike the upper wing, the disc area moment of inertia is the greatest on the axis of rotation/the vertical axis. And the starting torque can be generated by a gear-system to accelerate the disc from standstill to operating speed, which is very small. The gear-system can be built between the shoulder and disc, and it can generate high starting torque because the teeth are designed interlocking and therefore slip-free.

Even though the plain bearings are lightweight due to their compact design, they combine high resilience, break resistance, and good damping properties. They are also tolerant towards the contamination, therefore little sealing effort is acceptable. They are attractive for the costumers with their lows costs of the installation and connection structure such as housing and shafts. In our case, they are in low-speed operation but it is not a big problem because of their corrosion-resistant properties.

One radial spherical plain bearing (GE 240 ESL-2LS-SKF)(5) and two thrust plain bearing (GB/T 9162-2001 GX200S)(6,7) are selected. It is a suggested combination of a radial and a thrust spherical plain bearing (link[48]). The thrust plain bearings can mainly absorb axial loads, but they can also tolerate radial loads, which should not be greater than 50% of the axial loads. A combination of an axial bearing and a radial bearing is possible for the higher radial loads condition.

If the upper T-shaft(3) would be designed as an extension of the disc, the manufacturing and also transporting of the disc would be much harder. That is why the upper T-shaft is designed as an extra part to the disc and it is fastened with 4 screws to the disc. It allows made the montage easier. (fig.3.19)

In this case, the axial movement has to be secured in both direction, that is why the second thrust plain bearing(7) is used to hold the disc. This second bearing blocks any upward movements of the disc. But another problem was the second disc position related to the first one. The upper thrust plain bearing is resting on the disc and blocks the downward movements. The lower thrust plain bearing should block the upward movements. That is why a hole is drilled in the bottom of the disc so the bearing could be attached there. The ledge between these two bearings blocks the movement of the bearings. And then a cover(lower T-shaft(4)) is designed to fix the lower thrust plain bearing there. The lower T-shaft is fastened with 4 screws to the upper T-shaft.

3.3.3 Joining the Lower Wing to the Shoulder

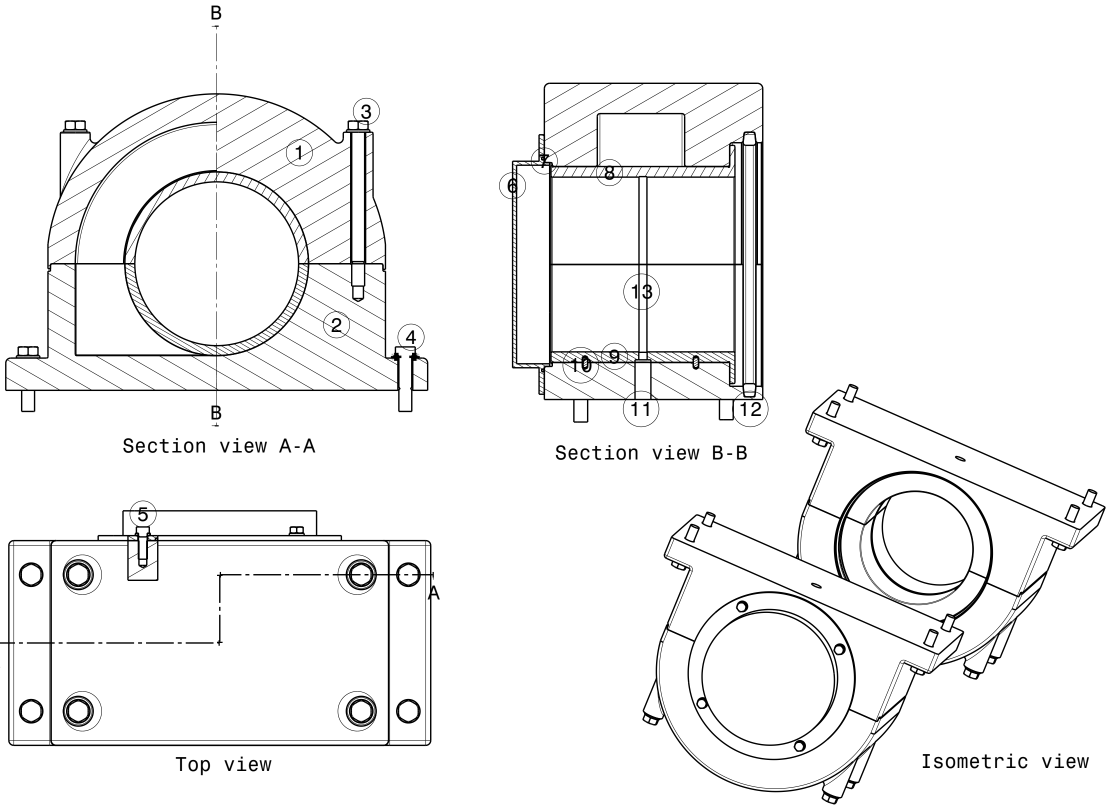

Figure 3.20: Lower wing - Plain bearing

1. *Upper plain bearing block housing*, 2. *Lower housing*, 3. *Screw* 670 *M*52 (4 *pieces for each housing*), 4. *Screw* 260 *M*52 (4 *pieces each housing*), 5. *Screw* 130 *M*36 (4 *pieces for one housing*), 6. *Housing cover*, 7. *Water seal O − ring*, 8. *Upper main bearing shell*, 9. *Lower main bearing shell*, 10. *Cylindrical pin*, 11. *Oil supply hole*, 12. *Mechanical water shaft seal ring*

The radius of the lower wing's shaft is 330 mm. The rolling bearings are much more expensive than the plain bearings for this large radius. Also, the lower wing does not have to move that often as the upper wing, that is why even they are in low-speed operation, The use of plain bearings is still suitable for this application.

The bearing for the lower wing should also absorb axial forces in addition to radial forces, that is why the collar bushings also should be used. Two-piece plain bearings are more often used for large diameters. Therefore they(8,9) are designed and the housing(1,2) as well in two pieces.

The propeller is mounted on the lower wing, therefore the propeller shaft forces are transmitted into the lower wing via the shaft line. These forces create a vibration on the joint. The vibrations induce micro-movements in the contact surfaces by rolling bearings and that can lead to damage to the rolling elements and running surface. The plain bearings are a better choice than rolling bearings in situations with vibration, because of their no digging in, no rust, and no false brinelling/corrugation properties. Corrugation is bearing damage caused by fretting.

POM/maintenance-free plain bearings are suitable for this operating condition because they can operate with minimal lubrication for a long period of time, which means minimal maintenance in difficult operating conditions. Most of them are build with the four layers, which are copper coating, steel backing, sintered bronze layer, and the POM. The grease is stored to retain the lubricant in the pores of the POM which is the top layer, .

The lower wing's plain bearings work in lubrication in the mixed friction range because the lower wing does not have the continuous motion in the rotation axis, which follows angular velocity. The friction produces heat, that is why heat dissipation is an important topic for the plain bearing housing. The plain bearing housings are very often manufactured from grey cast iron or nodular cast iron, which have high strength and best heat dissipation (1,2). Therefore these materials can be used for this case. 3.20

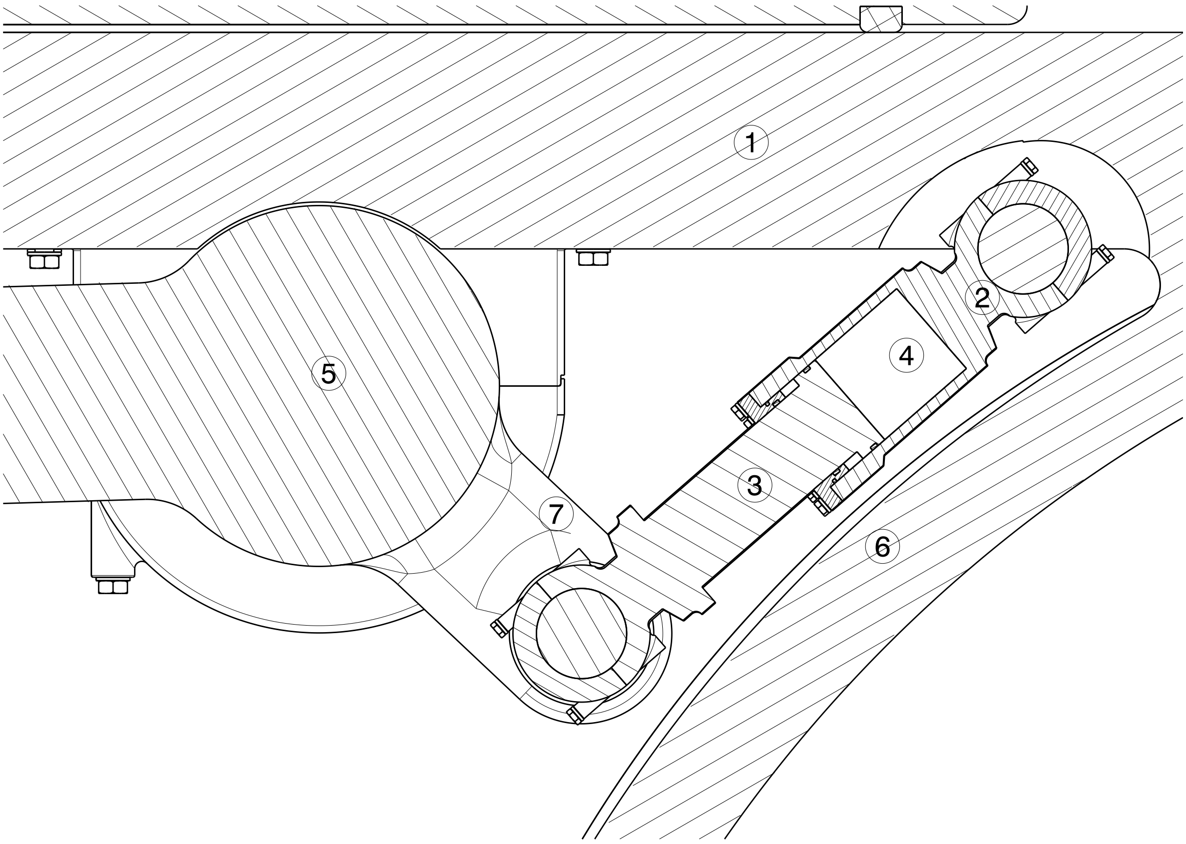

Figure 3.21: Lower wing - Hydrolic cylinder

1. *Shoulder*, 2. *Cylinder base with top and cylinder head* (*Cylinder head with buffer seal and head static seal*), 3. *Piston rod with piston seal*, 4. *Hydraulic oil*, 5. *Lower wing*, 6. *Main hull*, 7. *Lever arm*

The double-acting hydraulic cylinders(2,3,4) provide the rotary motion of the lower wing on its rotation axis. These double-acting hydraulic cylinders have two active directions of movement and this feature gives the necessary motion range for the lower wings. The cylinder base(2) is attached to the shoulder and the other side to the lever arm of the lower wing(5). The hydraulic cylinders generate linear movements, that is why the lever arm(7) is designed to convert the linear motion into the rotary motion. The moment, which is generated from the cylinder, is calculated by the force, which is acting on the lever arm, times length of the lever arm if the force acts to the lever arm with the 90° angle. If the angle between the hydraulic cylinder and the lever arm is less than 90° or more than 90°, the moment decreases.

3.3.4 Internal Structure of the Upper Wing

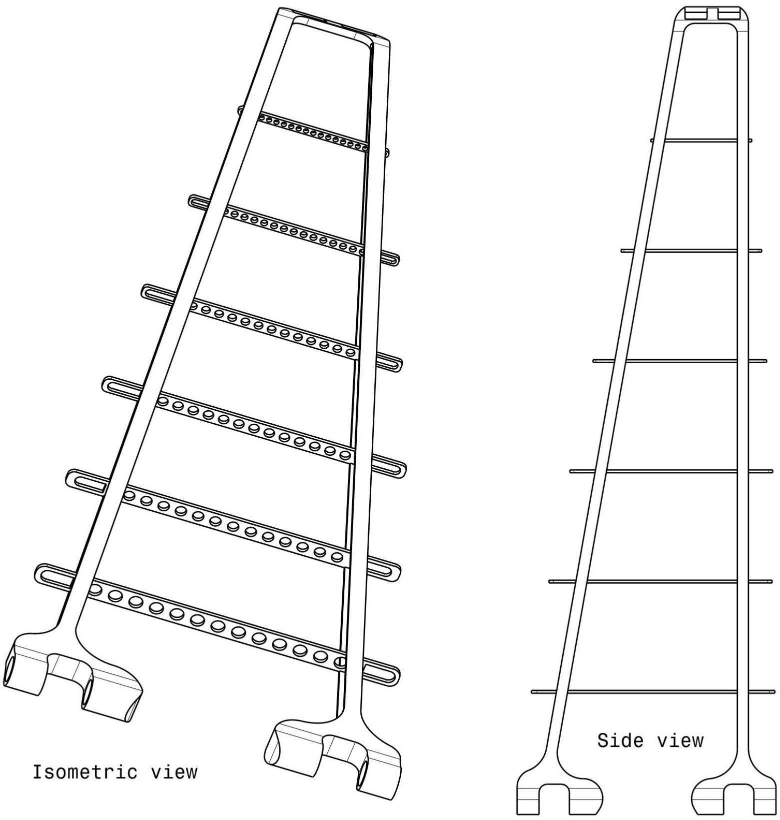

Figure 3.22: Internal Structure of the Upper Wing

Years ago the wings and fuselage frames were made of bamboo material, but the bamboo was not exactly suitable for the reducing air resistance for high speed, because of its round cross-section. These frames were shaped and stiffened with wires to maintain the required shape and the necessary strength. As the wing technology is developed the thin wings were replaced by thicker wings, which uses an H-profile beam (I-profile spars) for its frame structure. They generated more lift via using more powerful wing spars. In the aircraft construction, they started to use the corrugated iron for the outer skin of the wings and fuselage. These new design could not maintain the necessary strength in high air resistance, that is why they invented the box spars in conjunction with smooth metal paneling to maintain very high loads. The box spars are not really needed for the upper wing's frame because of its light carbon fiber skin.

The wings should be able to carry their own weight and the loads, which are occurring during the sailing. These loads can be categorized into 3 main groups. The first group would be its own weight, the second one is the wind load and the last one is the joint supporting forces of the bearings and the rope pulleys at the top of the wing. In our case, the supporting forces of the rope pulleys are critic because of their location point. As we have learned in the previous sections this has some critical issues.

The Internal Structure of the Upper Wing (fig.3.22) consists of a frame made of two main support I-profile spars and 6 transverse ribs/metal wing ribs, which is covered within some sheets of carbon fiber skin. These I-profile spars absorb the forces and bending moments, and the transverse ribs and the sheets of carbon fiber skin support the spars and spread the pressure. This construction can be further reinforced via using skin stringers. The skin stringers are stiffeners, which run in the longitudinal direction of the wing and are attached to the frame. They extend from the section, where the bearing shaft is fastened with the upper wing, to the tip of the wings, where the rope pulleys are located and are connecting each other at the tip of the wing. The connection point of these spars is where the rope pulley handle arms are located. These two spars are connected to each other also with these 6 wing rips to increase the strength of the upper wing. On the other end, where the bearing shafts are fastened, the body should be designed strong enough to be able to hold the supporting loads. We had the same outcome from ANSYS topology optimization in the sec.3.2.2 This structure should keep the upper wing in balance.

After the frame is designed in CATIA, aluminum is selected as the material of the frame. And then the analysis manager should be opened up to generate a mesh for finite element analysis. As we learned in the previous subsection, to have a better and more detailed result, we can adjust the nodes and elements function to have smaller and higher-order (linear, quadratic, etc.) elements for meshing. A finer mesh can reduce the processing speed very much. That is why selecting the optimal element size is very important. In CATIA from the linear or parabolic options, the parabolic elements are selected, because they are more accurate especially for stress calculation than the linear elements. In this analysis parabolic elements are selected. After deciding the size of the elements, the boundary conditions for the rolling bearings at the bottom of the wing and for the rope pulley at the top of the wing are added to fix the body.

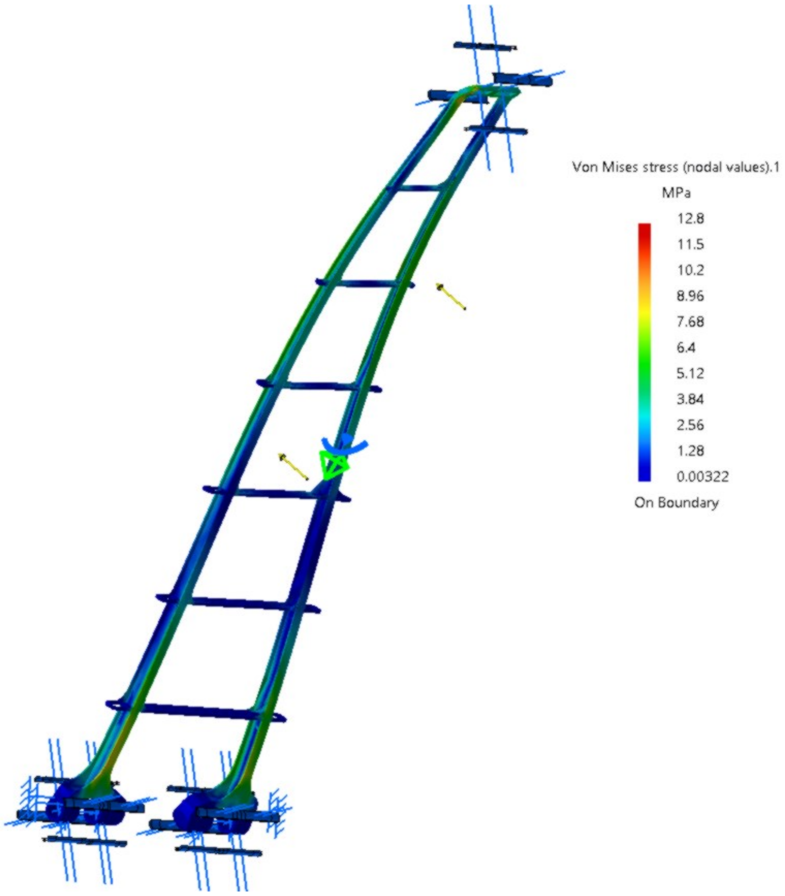

Figure 3.23: CATIA - von Mises stress - Upper wing

In the fig.3.23 we see the frame of the upper wing, which is designed in CATIA and then analyzed in CATIA. The structure is a 14m-long aluminum frame and weights 2.5 tons. As mentioned before, aluminum is chosen as framing material because of the low density, good mechanical properties, and it is suitable for various process methods. It has a tensile strength of 60 to 95 N/mm^2 and a 0.2% proof stress of at least 20 N/mm^2. In the stress scale, we see the maximum pressure, 12.8 Mpa (12.8 N/mm^2), which occurs under 2,370 N/m^2 pressure on the surface of the two main support I-profile spars with the surface area of 6.2 m^2. If we convert the pressure on the two main spars to the force, it would be 14700 N (14.7 kN). The wind force was calculated to be 14,700 N (14.7 kN) with the factors, that occurs during a bad weather condition. The frame of the upper wing will be covered with some sheets of carbon fiber skin and it will make the wings much stronger. Therefore the maximum pressure is not critical for the upper wing structure but this calculation can just give an overview of the situation. More detailed calculations such as dynamic carrying capacity analysis should take place to have the result near to real quantities. The natural frequency analysis is also very necessary for the upper wing design to identify its resonant frequencies because the risk of mechanical resonance can be very dangerous for a body, which is 14 meters long.

3.3.5 Internal Structure of the Lower Wing

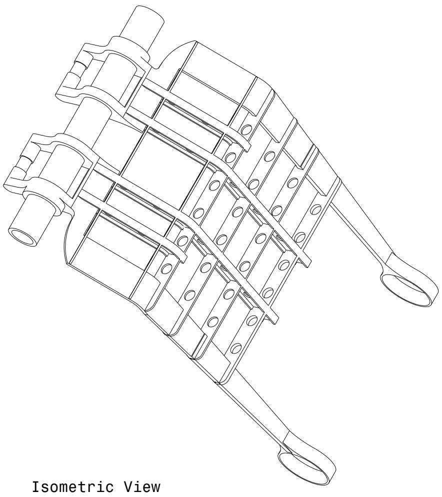

Figure 3.24: Internal Structure of the Lower Wing

The frame design was discussed in the subsec.3.2.1. The topology optimization has given us some useful ideas on how the frame should be designed. The first awareness we set from the cross-sections' pictures, which are the result of the topology optimization, was that the shafts for the plain bearings and the handles for the hydraulic cylinders can be hollow shafts to reduce the mass while the strength of the frame stays the same. The second observation was the upper section of the wing should have a stronger/denser structure than the next/lower section of the wing. And the third observation was the two lines of density moving from up to down at the middle of the structure. The two main I-beams at the middle of the frame, which are fixed at the beginning of the frame and go on towards to the lower part can take care of the issue. And to get a stronger structure at the upper section, 2 more I-beams are added, which also cover the twist point of the frame to strengthen the weak point. More rips are added on the lower section as well to stiffen the area to aviod the lower wing deformation because this part will experience water resistance.(fig.3.24)

In fig.3.25 we see the frame of the lower wings, which is designed in CATIA and then analyzed in ANSYS. The structure is around 9m-long aluminum frame and weights 10 tons. As we remember the aluminum has a tensile strength of 60 to 95 N/mm^2 and a 0.2% proof stress of at least 20 N/mm^2. In the stress scale, we see the maximum pressure, $1.3448 * 10^7$Pa (13,448 N/mm^2) for sailing conditions, which occurs under the load of the one-ton electric motor and a given water resistance. If the yacht is going with its motors, the drive thrust of the electric motor has to be taken into account.

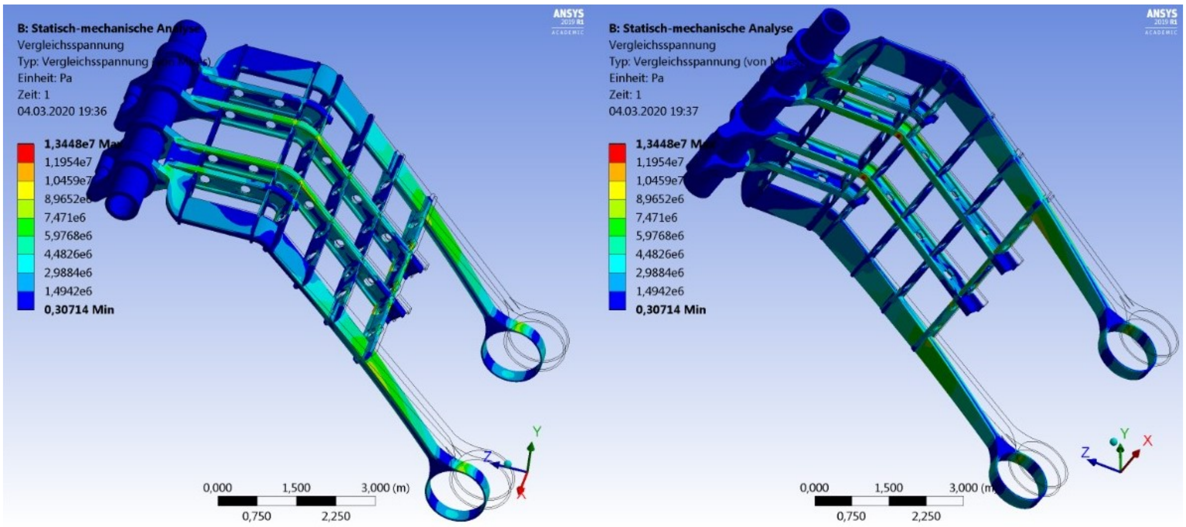

Figure 3.25: ANSYS - von Mises stress - Lower Wing

In this case, how fast the yacht is going is one of the parameters to calculate the external forces on the lower wing. The frame of the upper wing will be covered with some sheets of carbon fiber skin and it will make the wings much stronger. Therefore the maximum pressure is not critical for the upper wing structure but this calculation can just give an overview of the situation. More detailed computational fluid dynamics calculations are needed. We can also see the red color, which represents the max pressure, right under these two main I-beams at the twist (fig.3.25) the part is taken into the circle in red).

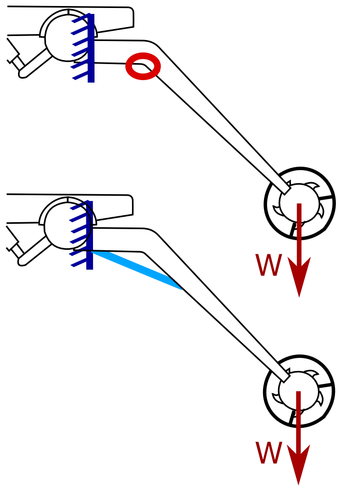

Figure 3.26: Lower wing stiffener

This frame is too heavy (10 tons) for the purpose of holding an electric motor, which adds one ton extra weight on the side of the boat. This problem of the lower wing can be solved. A stiffener (which is shown in the fig.3.27 in the light blue color) can be used to strengthen that point. This stiffener enables the frame to be designed lighter but this modification would spoil the elegant look of the lower wing. It is a good looking extension arm to hold the 200 HP electric motor on the side of the boat.

3.3.6 Mass Moment of Inertia of the Volitan

The mass moment of inertia of the Volitan yacht design is greater than the usual yacht designs because of its upper wings and lower wings. The more inertia it has, the greater tendency to resist changes in its state of motion. This gives a better sailing comfort.

We have mentioned this subject in subsection 3.1.2 at the theoretical level. In this subsection, we will calculate the ratio of the difference between the moment of inertia with the wings and without the wings. All the parts of the Volitan yacht are not designed in detail in CATIA, therefore the quantities we get from the design are not the exact values but nevertheless we can calculate the ratio of these two conditions to understand how big the change of the moment of inertia between the design with wings and without wings.

The total mass increases by 55.77%
The mass moment of inertia of the Volitan design on the x-axis with the wings increases 4 times than the design without wings.
The moment of inertia on the y-axis with the wings increases by 90.4%.
The moment of inertia on the z-axis with the wings increases just by 27.47%.
As we mentioned in the previous subsection on the x-axis we see the biggest difference due to the distances of additional bodies/wings to the center of mass.

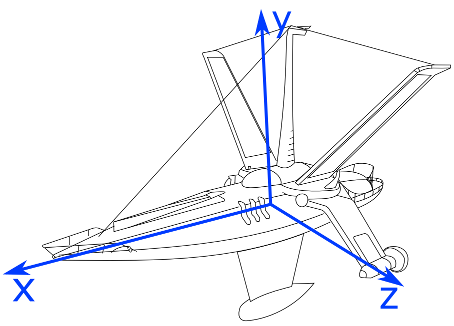

Figure 3.27: Volitan - Coordinate system

Is it beneficial? Is increasing the total mass by around 50% worth to have a 4 times greater mass moment of inertia. The increased weight would increase water resistance. Although it is not just about achieving greater inertia, it is also about having solar panels on the upper wings, which can move to get the best efficiency of solar-panels exposure. The upper wing's frame is also 4 times lighter than the lower wing's frame. The lower wings' advantages in maneuvering as mentioned above is significant, however, its ratio of performance to its costs makes the lower wing less attractive than the upper wing.

Chapter 4

Conclusions

The impact of carbon emissions on our environment and on us is an important issue. Limiting global warming to a 1,5° is essential for our world's future. And eco-innovation for logistics and transportation has a very important role to achieve a reduction in carbon emissions. The solar and wind-powered concept boats are one of the solutions for carbon emissions, which we can develop further.

The aim of this master thesis was to analyze aspects of the solar and wind-powered concept boats in more detail by analyzing the extraordinary example of the Volitan yacht design. The main factors, which are related to the solar and wind-powered concept boats in the introduction chapter are examined. This concept for boats is new and has only a few examples. Therefore, it needs more research to get to a certain level. For that reason, investors should be aware of this concept, so that the engineers can find funding for their projects.

Ship model testing in a ship model basin is not that necessary anymore because the CAE software can simulate the same tests, which were used to be done in the model basins. Nevertheless, the ship model basins are still in use for big projects such as a very large merchant ship projects or navy projects.

Solar power is a very useful way to generate usable energy from the sun for estimating small power consumption for the boat. Solar panels can not generate enough electricity for an electric motor as the only source of electricity. In this case, the batteries can be used to store the electricity for later to operate the e-motor. Tesla lithium-ion batteries are the best choice for this application because of its simple and effective technology.

The heeling moment is one of the obstacles to achieve higher speeds. The heeling moment can be balanced out with a wide hull design like a catamaran hull or with the use of hydrofoils. The boats with hydrofoils have still some stabilization problem but there are many investigations on this topic for better stability.

Wingsails are getting more attention in the last ten years. They can be built taller because of their strong structure and therefore they can sail upwind higher to sail faster. Their purity of engineered cross-section profiles allows for higher speed and easy control of the wingsail. These cross-section profiles are assorted. The wingsails with the wing flap are the new favorite sails at America's Cup competitions.

The researches shows that the hull design has a big impact on the max speed of the sailing yacht. Therefore, the hulls, which look like an aircraft's fuselage, are used more often to reduce the wind resistance for the maximum speed.

The benefits of CAD-Computer aided design and CAE-Computer aided engineering are lower product development costs and development times, that improves product quality and lifespan. CATIA and ANSYS are one of the best programs for product development. ANSYS was recommended in this study for FE-analysis because of its excellent material analysis methods such as topology optimization.

The researches and analyses, which are done in this thesis, gave the following result about the Volitan yacht design's parts:

The topology optimization can give the best option to reduce the weight and redesign the product. The parts, optimized by topology optimization were usually not suitable for manufacturing. The parts' shapes after the optimization were like spider-webs or shattered rocks. They did not have smooth surfaces. Therefore, some design corrections should be done to enhance the surface quality of rough topology data. These shapes can be printed out with the 3D-printers after enhancing the surface quality. The 3D-printer technology has lots of aspects ready to be developed.

The lower wing is giving some advantages in the mass moment of inertia and boat maneuvering but it has expensive parts such as the big plain bearings, hydraulic cylinders, etc.. The frame of the lower wing, which is made of aluminum, is strong enough for its condition with two main I-profile spars, two more additional I-profile spars, and 6 transverse ribs.

The mobility of the upper wings allow the solar panels on them to get the best angle to convert sunlight into electricity but on the other side, the mobility requests 2 DOFs, and to get these DOFs, 9 expensive bearings are needed for each wing. Also, the rope pulleys, which are located at the wing's tip point, bring the risk of mechanical resonance because of their location. The frame of the upper wing, which is also made of aluminum, is stiff enough with two main I-profile spars and 6 wing rips. These frames of the upper wings should be covered with some sheets of carbon fiber skin to have light and strong parts. Carbon fiber is more expensive than glass fiber, even though its mechanical performance is not that much better than glass fiber. But the Volitan yacht design is a luxury 32 meters yacht, that is why the choice of carbon fiber would not be an exaggeration.

My master thesis can be used as a handbook of the solar and wind-powered concept boats for the investors, who want to build a functioning eco-friendly sail yacht. The focus is on informing the people and making their work easier by giving them a book, which explains all the important aspects to develop a design of their own.

After conducting the examples and experts interviews, it shows that eco-friendly designs are very famous in green design competitions and win tons of awards. However, most of them cannot find funding to build the actual design because the costs of manufacturing of these designs are very high.

List of Symbols

x	position $[m]$
v	velocity [m/s]
t	time $[s]$
F	force $[N]$
W	weight $[kg]$
a	distance $[m]$
h	height $[m]$
b	distance $[m]$
r	righting arm $[m]$
u	flow speed [m/s]
ρ	density [$\mathrm{kg/m^2}$]
ν	kinematic viscosity [$\mathrm{m^2/s}$]
μ	viscosity [$\mathrm{kg/(m * s)}$]
g	characteristic external field [$\mathrm{m/s^2}$]
L	characteristic length $[m]$
A	area [$\mathrm{m^2}$]
P	pressure [$\mathrm{N/m^2}$]

Abbreviations

CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Comupter-Aided Manufacturing
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
LES	Large-Ebby-Simulation
RANS	Reylnolds-averaged-Navier-Stokes
EU	European Union
HP	Horsepower
2D	Two-dimensional Form
3D	Three-dimensional Form
PV	Photovoltaic
USV	Unmanned Surface Vehicle
DOF	Degree of Freedom
FEM	Finite Element Method
PML	Product Lifecycle Management
STL	Standard Triangle/Tessellation Language
NC	Numerical Control
STEP	Standard for the Exchange of Product model data
RM	Reaction Moment
HM	Heeling Moment
WL	Waterline
G	Center of Gravity
B	Centre of Buoyancy
K	Keel
GM	Metacentric Height
GZ	Righting Arm

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