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Dynamic response analysis of a catamaran wind turbine installation vessel with focus on the transportation stage

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NORDIC MASTER OF SCIENCE IN MARITIME ENGINEERING AND TECHNOLOGY

Master Thesis

Dynamic response analysis of the catamaran wind turbine installation vessel during transportation

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Preface

This is my Master thesis for, Marin engineer, Ocean Structures Specialization report at the Department of Marine Technology, NTNU; together with the Danish university,DTU. Has been one semester of working, from January until June 11th 2018. The objective of performing the dynamic analysis for a novel catamaran installation vessel concept for the installation of pre-assembled rotor-nacelle-tower systems onto bottom-fixed or floating support structures proposed at the Research-based Innovation Centre – Marine Operations in Virtual Environments (SFI MOVE).

After a lot of literature has been carefully reviewed, and several analyses among stability, dynamic and structural, this document will work as a base to develop a complete and efficient design, than can reduce the time for developing offshore floating wind farms.

This report should provide the reader with a better understanding of the different techniques and technologies that are being used in the maritime operation phase of transportation, and which ones can be applied for the transportation of full assembly wind turbines.

Furthermore, my intention with this study was to become an 'expert' on the current methods in offshore transportation, to get a better knowledge of multi hull vessels, guidelines and criteria that need to be accomplished. As well, to define a step by step on dynamic analysis in a clear and illustrative way so other students can be benefit of it.

This was done successfully.

The primary objective for the master thesis at the time of writing this project is to provide a different solution to decrease the cost and operations time at the transportation phase of the offshore wind turbines by the use of the catamaran installation vessel.

Although, some thoughts are discussed in the conclusion chapter.

Acknowledgements

Furthermore, I want to thank all the help that has been offered to me.

Thanks God, Mexico and my Family that are always there.

I would like to thank my supervisors team;

Takk Zhiyu Jiang that has been someone who can trust and always helpful when I have questions a couple of times during the year.

Tak Yanlin Shao, for always keeping an eye on the work situation, even when you are at a distance.

Takk Zhen Gao for constantly follow up on my work being available and helpful during the process, to give me the freedom to analyze such an interesting project.

Tak to my teachers, the UV ones, the DTU ones, NTNU ones and the ones before.

Tak to all that without know help in the journey (include the ones in YouTube who explain some topics quite awsome).

Tak-k to my friends, Nordic ones, Kokedal ones, Nul-Kryds ones, Mannhullet ones, Office ones, DTU ones and NTNU ones, Moholt ones, and the ones that always support me from Mexico, was a ”Fantastisk” couple of years.

——————- ”Det finnes ikke dårlig vær, bare dårlige klær.”——————
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Abstract

The United Nations have agreed on the Sustainable Development Goals for the world where one of them is to achieve affordable and clean energy for the whole world for which wind energy would be a good option. Additionally, the price of wind power generation has decreased its production costs and its demand has grown. Offshore sites are the best option to place wind farms since: the quality of the air for its energy use is better, there is a large free space to transport and maneuver with large structures, and the noise problem is avoided near populated places. Catamaran vessel designs have a superior capacity to transport loads with a high center of gravity, and that have a lower resistance to advance than mono-hulls. MOVE has proposed the design of a catamaran-type vessel to transport and install four fully assembled wind turbines. From design perspective of a vessel or marine structure, it is important to predetermine its behavior when it is subject to environmental conditions, such as wind and waves in different directions.

The objective of the thesis is to present how the dynamic analysis of the catamaran-type wind turbine installation vessel system with 4 wind turbines full assembly on board has been performed, to know its behaviour in terms stability, sea-keeping motions, and stress for a sea-fastening, on an early design stage.In addition, applying and, if possible, ensuring the fulfillment of the corresponding criteria.This, to contribute to the set of analysis of catamaran vessels as solution for the future of wind-turbine transportation that has been carried at SFI-MOVE.

The shape of the vessel was improved, the offset table lines smoothed and the mesh selected for the specific wave length. From this it was found that the stability of the ship fulfill the stability criteria selected for the ship, since there is no official criteria for the particulars of the vessel, using the IS code 2008, part A and B, criteria that can be consider more than sufficient for this type of marine operations has been succeed.

For the dynamic analysis the method stated in the correspondent chapter was followed and as a result the displacements, velocities and accelerations where obtained, where it was shown that the values art the nacelle, where more than the 0.3g, which is the design limit parameter.

The sea fastening was design for beam and Shell elements, the beam elementss can be know the displacement but no the stress. For the shell elements the sea fastening support in x and z the accelerations but fail in the y direction.

In conclusion; By performing a dynamic analysis, accurate accelerations can be obtained. This entails a reduction in risk and an increase in efficiency for all marine operations and therefore a reduction in costs. And, additional systems should be implemented to reduce the accelerations, since, they are more than the tolerated for the design of the WT machinery.

Keywords

Transportation; Sea Voyage; Marine operations; Wind energy; Dynamic Analysis; Wind turbine.

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List of Acronyms

IMO	=	International Maritime Organization
DNV-GL	=	Det Norske Veritas (DNV) and Germanischer Lloyd (GL) merge
WT	=	Wind Turbine
ASD	=	Allowable Stress Design (effectively the same as WSD)
WSD	=	Working Stress Design
DP	=	Dynamic positioning system
Btoe	=	Billions of toe
toe	=	The tonne of oil equivalent
AHTSV	=	Anchor Handling Tug Supply Vessel
T&I	=	Transportation and installation
CG	=	Center of gravity
MWS	=	Marine Warranty Survey
Tpop	=	Planned operational Period
LRFD	=	Load and Resistance Factor Design
ASD	=	Allowable Stress Design (effectively the same as WSD)
WSD	=	Working Stress Design SDG = sustainable development goal SDG7 = SDG number 7

Chapter 1

Introduction

1.1 Scope

Trough the document you will find the procedure that was carried to perform the dynamic analysis of the wind turbine carrier catamaran type vessel, which is meant to transport four full assembled wind turbines. The work was carried in three parts, the first one is related to the pre-procedure, how the input values were selected and how an improvement of the shape of the ship was performed to ensure the intact general and severe survival condition stability criteria. The second is related to the hydrodynamic analysis where the stability and the motions analysis were performed. In this part, the explanation of the elements that take part of the stability and dynamic analysis are shown for some of the cases. The results are given for the motions, velocities and accelerations on the vessel for different points of interest as the base of the wind turbines and the center of gravity of the nacelle. Followed by the third part, a structural analysis of a frame type sea-fastening is shown, using as input the accelerations from the previous part.

Figure 1.1: Catamaran WT Installation Vessel.

Closing, it can befind the chapters for the discussion of the validity of the results and the conclusions of the work.

This chapter starts with the motivation of the master thesis and a general overview of the wind industry growth. From the actual world concern, to, general wind turbines economics and offshore wind energy industry.
Then, describes in a general way, the wind turbines and their classification; marine operations are defined in a general way and subsequently in a particular way the "sea Voyage"; mention is made of the ideas and proposals that currently exist to improve the efficiency of wind turbine transportation; The advantages and disadvantages of using a catamaran for the transport of wind turbines are analyzed; it is defined, the different analyzes necessary for the transportation of the wind turbines; and, an approximation is made to the different rules, procedures and recommended practices for the transport of marine structures using the DNVGL class company as an example. Closing with the structure of the Msc thesis.

1.2 Objective

Present how the dynamic analysis of the catamaran-type wind turbine installation vessel system with 4 wind turbines full assembly on board has been performed, to know its behaviour in terms stability, sea-keeping motions, and stress for a sea-fastening, on an early design stage.
In addition, applying and, if possible, ensuring the fulfillment of the corresponding criteria. This, to contribute to the set of analysis of catamaran vessels as solution for the future of wind-turbine transportation that has been carried at SFI-MOVE.

1.3 Motivation

Can we do transportation and installation of offshore wind turbines with lower cost? A new concept of catamaran-type wind turbine installation vessel was proposed at the Center for Research-Based Innovation: Marine Operations in Virtual Environments (SFI MOVE).

The novel catamaran installation concept is intended to be used in fixed or floating support systems and used to transport and install a maximum of four pre-mounted nacelle-rotor-tower systems in a single trip.

These wind turbine assemblies are attached to the platform using sea fastenings during transportation. Then, a lifting mechanism moves the assembly along the longitudinal direction of the vessel and placing it on the support structure, assisted by a dynamic positioning system (DP).

Previously, the dynamic response analysis was performed in SFI MOVE and NTNU, with a focus on the installation stage, but no work has been done in the transport stage.

In general, the proposal is aimed to increase the efficiency of the transport operations and reducing the number of lifts in the installation of wind turbines, reducing the cost and risk at the offshore site. Then, contribute to the progress of the offshore wind turbine industry.

1.4 Background

1.4.1 Global Concern

The world, through the United Nations, has set out to achieve a change that will benefit everyone by the year 2030. This will be achieved through the application of the seventeen global sustainability goals. A series of effective partnership and peace actions can achieve a global balance between the economic, the environmental and the social. Looking at the world holistically, equal opportunities for all can be achieved. The agenda of the United Nations is an ambitious project, which requires different actors and international organizations to invest in developing and sharing knowledge that achieves development for the people and prosperity, protecting the planet and the natural resources. It is necessary that the industries modify their behavior, understanding the interdependence that exists between the different factors that affect the world society.

The SDG7, is about to achieve access to affordable, reliable, sustainable and modern energy for all. Companies and companies have carried out a large number of activities and modifications in relation to achieving compliance with this goal; however, progress has been relatively slow. With what has not yet been achieved, the first target is to double the global rate of improvement in energy efficiency throughout the world.

”Globally, 85.3 percent of the population had access to electricity in 2014, an increase of only 0.3 percentage points since 2012. That means that 1.06 billion people, predominantly rural dwellers, still function without electricity. Half of those people live in sub-Saharan Africa. September 2015". [16]

So, the efforts to develop methods for the installation of infrastructure that allows to generate energy more efficiently on the planet is a current issue of vital importance.

Figure 1.2: Global sustainability goals [17].

1.4.2 Energy Demand

Electric power is a resource that is growing every day. Countries use technology that modifies society's lifestyle in a general way, from large factories with a greater number of robots to families where the increase in appliances consumes the energy that is generated daily. Additionally, a large increase in energy demand is expected from highly populated countries such as China and India. The United States does not expect a large increase, but its current consumption is already enough to position it in the second country with the highest consumption for the year 2040 behind China [13].

Statoil has presented in its "Perspectives 2017" three possible scenarios. The first is that all countries comply with the agreements made and we aim to ensure that industries, companies and people take precautions and minimize the needs and waste of energy. Secondly, the prospect of meeting the minimum set by agreements in which a balance is sought among all. Finally a scenario in which there is rivalry between countries, where some countries spend a the most of resources, which are more than they produce. The same report shows that the demand for gas and oil to satisfy the needs of mankind as now, will continue to increase and even in the best scenario, it will not satisfy this demand so the need for energy alternatives is a fact, and a great business opportunity. Given the above, there is great global potential for solar and wind power among others. [**stat˙per**]

It can be perceived internationally, with the SDG7 in mind, that countries are modifying the demand for energy in relation to the type of fuel used to obtain it. Currently a large amount of coal and hydrocarbons is used for the generation of electricity, however, organizations and companies such as IEA [13] or DNVGL [6] perceive that around 2030 the generation of electricity by low-carbon will exceed those mentioned above. And by 2050, the pair of wind and solar energy generation sources will represent around three-quarters of the market, so that companies are already changing their market model to adjust to the competition and demand that there will be. The aforementioned is being achieved as society demands more strongly to be sustainable companies day, so they are investing in research for better alternatives in conjunction with different organizations.

1.4.3 Renewables Cost Reduction

Although fossil fuels remain, and will be the main source of energy for the next few decades, the application of renewable energy has grown faster than expected, partly as a result of insecurity in oil prices and the international interest in reducing climate change.

Comparing the cost of generating power has been a topic of interest in recent years because to measure whether one type of generation is really beneficial compared to another is a great turning point for decision making both governments, entire industries or even individuals. The complexity of this comparison is related to the fact that production costs are significantly different. At the end of the production line when energy is obtained, it is possible to measure how much has been obtained and compare it with the investment made to obtain it, so a comparison in dollars or euros per kilowatt-hour (kWh) or megawatt-hour (MWh) It is the most usual.

To achieve this comparison, the levelized cost of electricity (LCOE) has been defined. This comparison includes factors such as initial investment, maintenance, and fuel among others. [26]

Therefore, the LCOE has become a measure applied to an energy source which is focused on comparing the different methods of electricity generation in a consistent manner. This provides an economic evaluation for the total average cost of said source of power generation with which one can decide whether to build or operate an active energy generator with the knowledge that throughout its life by the total production of energy of the asset during that life is profitable. If the cost of generating a type of energy is too high in the long term, however ecological it may be, it will not be a viable option from the investor's point of view. The LCOE also helps determine the average minimum cost at which a company dedicated to power generation can sell the electricity generated, in order to reach a point of balance for both the company and the consumer throughout the life of the project.

Currently, the LCOE's direct comparison of the different forms of energy generation in relation to the LCOE of fossil fuels is used to determine the advantage of one over another.

In the last 8 years, there has been a great investment in the development of renewable energies. Energies such as biomass, geothermal and hydro-power have had an increase in their relatively low LCOE, but projects have been created that have been better than the generation with fossil energy.

A great advance in solar energy has significantly reduced the LCOE of the same, which has gone from highly expensive projects with reduced production to more economic projects that generate a greater amount of energy. Wind energy, both on land and offshore, has also had a decrease in its LCOE, although it has not been as big a difference as with solar, it maintains a high generation of projects that with relatively the same investment is generating energy more efficiently, but there are still many areas for improvement. Such is the example of the Norwegian company STATOIL, which in partnership with MASDAR, has managed to reduce the cost of installing the Hywind Scotland wind farm by 60 to 70 percent compared to its Hywind Demo project [23]. The power of wind and solar have the challenge of being better than the energy from fossil fuels to get most of the market. [14]

1.4.4 Wind Energy Growth Trends

Europe is one of the main sites where wind energy has been developed and in which companies have invested large amounts in expanding knowledge of the subject. This has led to lower market prices and therefore improves its position in relation to the other ways of generation. During 2007, the generation capacity with wind energy surpasses the energy produced by fossil oil in Europe, which continues to decrease. In 2016 it was placed as the second form of electricity generation in Europe, only below the gas that has remained relatively constant during the last decades competing and exceeding in 2010 the coal. The European growth of wind generation has been largely to the companies that continue to increase their capacity year after year, being in 2017 the largest in new installed capacity with 15,638 MW, reaching a total installed capacity of almost 170 GW. [8]

This is an indication that the world tends to see wind power as a plausible option for the generation of clean energy.

1.4.5 Offshore Wind Perspectives

Wind energy is at a time of important development and research because, as mentioned above, prices have fallen, allowing companies to invest in better ways to produce wind energy.

Wind generation is divided into offshore wind turbines and offshore wind turbines. The land wind turbines have the advantage of being in fixed places where access is generally simple so the maintenance and supervision of wind farms on land is easier, in contrast to offshore wind turbines where the environment is more aggressive, the materials they have a greater corrosion and access to offshore facilities require more complex means. The foregoing is reflected in the industry since on-shore wind turbines outnumber the offshore installations currently.

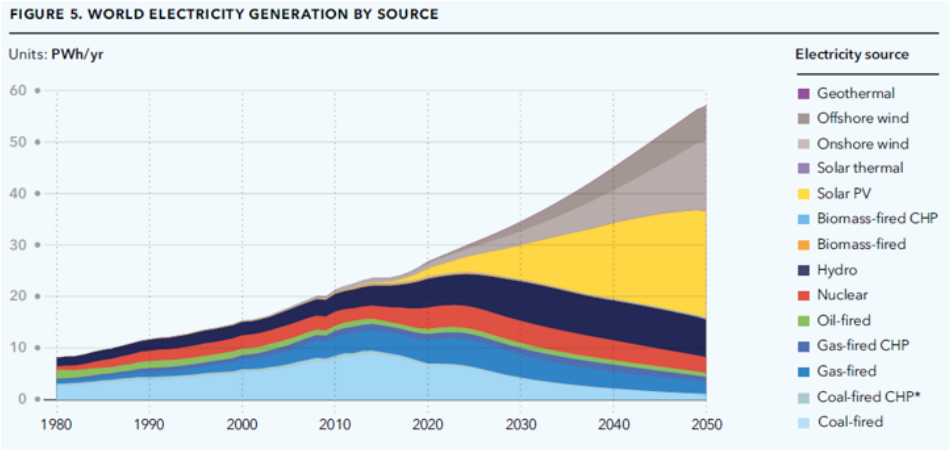


Figure 1.3: DNVGL- Wolrd electricity generation by source [6].

New Opportunity Areas

However, offshore wind turbines have two main advantages. The first is that when transporting wind turbines by sea, the amount of obstacles such as bridges and defined roads can be discarded; this leads to the transport of much larger structures or failing that, in a smaller number of pieces than those required to transport a structure on land. The second is that the average air power density goes from an average of 100 Watt per square meter on land against 400 Watt per square meter, which has the capacity to generate much more energy.

These new areas of opportunity are currently a possibility thanks to the investment of companies and organizations, which see a large area of opportunity. Such is the case of the Norwegian company STATOIL in which I quote:

”Offshore wind farms eliminate many of the challenges associated with onshore wind, and hold the key to exploiting an inexhaustible resource. Now that floating wind technology is mature and costs have started to come down, we expect to see exponential growth in floating offshore wind worldwide”.[23]

Additionally, not using habitable land or near towns where noise or visual disturbances may be caused increases society’s acceptance of this type of energy.

This has contributed to the expectation that the offshore market will continue to grow until it is placed with a third of the wind market around 2030 [6]

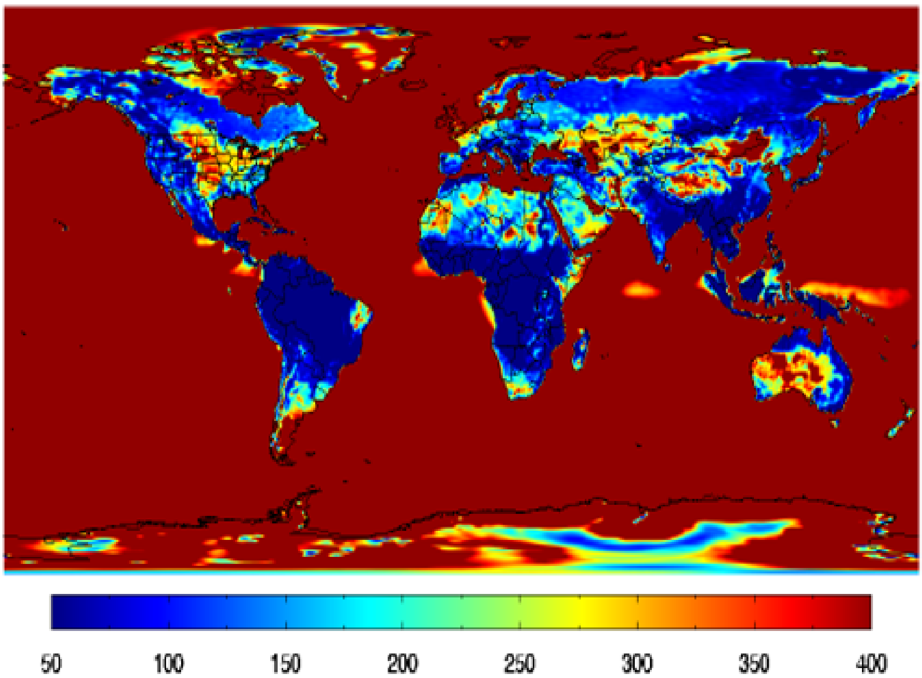


Figure 1.4: Annual mean wind power density at 50 m above the surface (Watt/m2) [20].

1.5 Literature Review

1.5.1 Wind Turbines

The different temperatures located in the regions of the world caused mainly by the translation around the sun and the rotation of the earth, produce zones with different atmospheric pressures. This causes the air in the atmosphere to circulate, generating the wind. Through the use of different mechanisms, man has been able to transform the kinetic force of wind into mechanical and electrical energy. Using the air, the navigation of sailboats is possible, or the rotation of blades connected to a rotor, such as those found in windmills and currently in wind turbines. In the case of the wind turbines, since the rotor is connected to the axis of the generator, the mechanical energy is transformed again, producing electrical energy.

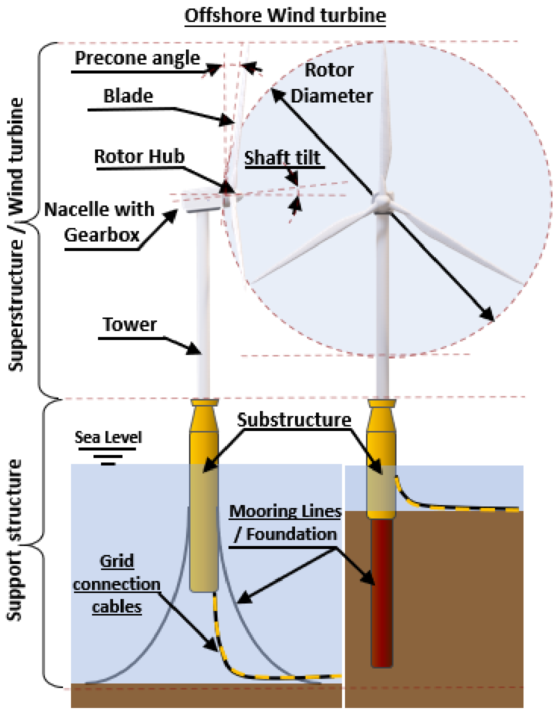


Figure 1.5: Wind turbine main parts.

Wind power systems can be defined in three general classification ways: Network connectivity; connected or independent. The installation characteristics; on land or offshore. And, the type of turbine; vertical or horizontal axis.

In relation to network connectivity, wind turbines can be found individually ”stand alone” or together ”Grid Connected”. A series of wind turbines is known as a power plant, wind farm or wind farm. These are composed of wind turbines, monitoring facilities, substations and transmission cables.

Wind turbines generally consist of a rotor and nacelle assembly, tower and support structure. Additionally, if the installation of the WT is located offshore, a substructure is required which serves as the basis for it.

Due to the above, the condition of the wind, the amount of available space or land and the availability of the network vary. This influences the configuration of the system, both in size and in the height of the turbine, the size of the blade and the number of sections.

The number of blades is also an important factor in the design, the structural analysis, the turbine capacity and the forces present in the system. Due to the balance of gyroscopic forces, the economic reasons and the efficiency of wind energy, most of the commercial wind turbines found have three blades in the rotor. Fewer blades cause a slower rotation when receiving less air and require more substantial use of the gearbox and transmission. In contrast, more blades add more weight to the structure so a stronger wind is required to move the blades. Therefore, it has been determined that the optimum number of blades is three, although this may vary according to the different designs and innovations in the system.

As stated above, and as it can be seen in the next figure the plan to select the three bladed wind turbine, is actually the best option.

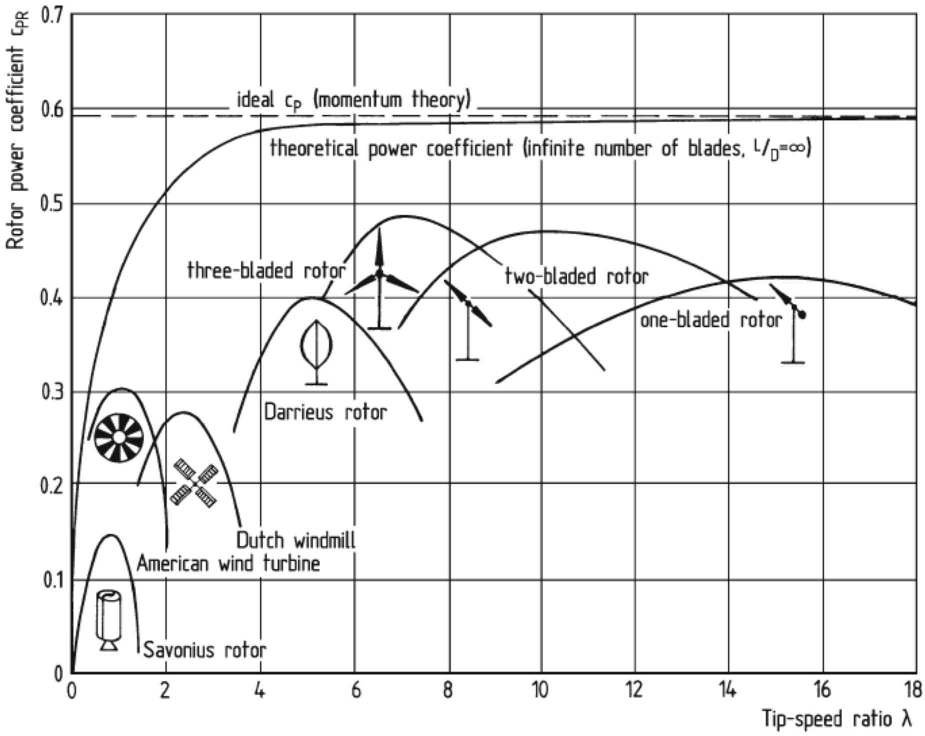


Figure 1.6: Erich Hau, power coefficient for different wind rotors. [12]

1.5.2 Offshore Wind Turbines

The main difference between onshore and offshore wind farms is the support on which they are placed. The wind turbine, of an industrial land-based wind farm, as general, has in its foundation a resistant concrete base. Marine bottom fix wind turbines have their foundations in the marine seabed. Or in the case of the floating wind turbines, they are collocated on a floating substructure. Both having a different variety of base types and construction materials. Wind farms are designed to meet the harsh conditions of maritime conditions such as the wave loads, the salinity of the sea and strong winds. That's why they must comply with a series of specific operational requirements that are additional to those cover by the wind turbines that are in land.

The use of floating substructures presents a great number of advantages such as the large amount of deep water available and the good quality of the wind, since there is a greater regularity of it at open sea, as stated above. As well as the fact that they can be standardized and manufactured in series. This does not leave the factor that currently floating turbines continue to have a higher cost for what entails large investigation to overcome the little experience there is for their installation (in comparison to fixed or terrestrial foundation and even in comparison with oil industry).

Several of the floating turbines that are installed today are under development and research. In the second half of 2017 was placed the first floating wind farm by the Statoil company. This wind farm has a capacity of 30 MW and is located 25 kilometers from the coast of Peterhead in Scotland, in an area ranging from 95 to 129 meters of depths. [23]

One of the biggest challenges of maritime operations is the transportation of the structures to site where they will operate. Which includes the transport of the foundation components, the substructure, the components of the turbine, the substations and the wiring among others. Taking into account that for a wind farm it normally has an amount of, for example, 111 wind turbines as in the Anholt (Denmark) [22] wind farm or the 88 wind turbines and 2 substations of the Sheringham Shoal wind farm (UK). In addition, that the logistics for the entire process of marine operations involved are long-term processes.

The saving of time and costs in any part of these activities can impact favorably on the whole operation, so the choice and development of better methods is essential for the growth of this type of offshore energy alternative.

1.5.3 Marine Operations

Bearing in mind that depending on the scope of work where you are, the authority and time, the definition of marine operations may vary. It is not the same if it is being defined from the military point of view, where it talks about the operations that the units perform at sea. Or from the point of view of a port where operations are summarized in the loading and unloading of containers and other goods arriving at the port.

Norwegian authorities had use also different definitions:
In general, the DNV classification society had it defined as follows:
Non-routine operation of a limited defined duration related to handling objects and vessels in the marine environment during temporary phases. In this context, the marine environment is defined as construction sites, quay areas, inshore, offshore waters or sub-sea.[2]
* Any operation conducted using Vessels offshore, inshore or at terminals ashore. [21]
* Any vessel operation conducted offshore. [21]

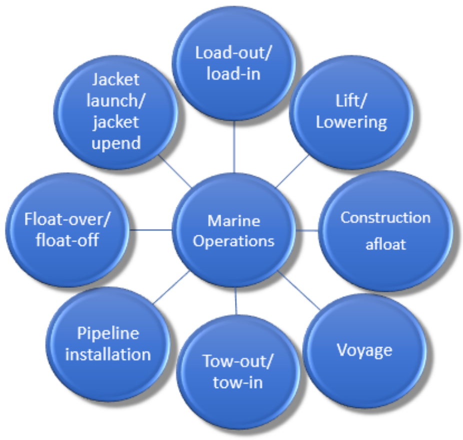


Figure 1.7: Marine operations.

Now that DNV has merged with GL, they have agreed that maritime operations generic term covers, but not limited to, the following activities which are subject to the hazards of the marine environment as stated in figure 1.7. [5]

a) Load-out/load-in:
Load-in: The transfer of an assembly, module, pipes or component from a barge or vessel, e.g. by horizontal movement or by lifting.

Load-out: The transfer of an assembly, module, pipes or component onto a barge or vessel, e.g. by horizontal movement or by lifting.

b) Voyage:
Voyage covers both towages and transport from one place to another.

Transport: The operation of transporting a cargo on a powered vessel.

Cargo: Where the item to be transported is carried on a vessel, it is referred as the cargo. If the item is towed on its own buoyancy, it is referred to as the tow.

Towage: The operation of towing a non-propelled barge, vessel or other floating object by tug(s).

c.) Lift / Lowering (offshore/inshore):

Lift: Pick up and move to a different position,raise to a higher position.

Lowering: Pick up and move to a different position,raise to a lower position.

d.) Tow-out/tow-in:
Towing inside or outside from a specific location, usually port.

e.) Float-over/float-off:
The operation of installation/removal of a structure onto or from a fixed host structure by maneuvering and ballasting the transport vessel to effect load transfer.

Float-out (off): The activities necessary to transfer an object from a dry construction site to a self-floating condition outside the construction site.

Float-over: A reversed lift-off. I.e. the activities necessary to transfer a vessel transported object onto land/ seabed supports by a vertical movement.

f.) Jacket launch/jacket upend: [3]

Jacket: A sub-structure, positioned on the seabed, generally of tubular steel construction and secured by piles, designed to support topsides facilities.

Launching: Activities comprising of the cutting of sea-fastening of an object resting on a specially equipped launch barge, skidding of the object along skid-ways and lowering into the water until the object is free floating.
Upend: The activities necessary to upend (rotate) a floating object.

g.) Pipeline installation:
Installation of any marine pipeline system for the carriage of oil, gas, water or other process fluids. It may be of rigid material or flexible layered construction.

h.) Construction afloat:
Construction operations meanwhile the structure or the systems for the operation are floating.

Transportation is consider part of a temporary state for the marine structure, and is part of the group of Marine operations.

1.5.4 Sea Voyage of Marine Structures

Voyage of marine structures include many examples, most of them are very different between one another. For example, there are the cases of the small or big jackets, which are used to being transported on large barges. A quite different example is the case of big spars that are towed with help of multiple OSV. Big fish farm cases, wind turbine assemblies and decks are just some examples of this. Apart of the special needs that each one of the cases need, there are some key steps that all the voyage should cover: Structure definition, route, type of sea voyage, vessel(s) selection, voyage or transportation analysis, securing devices and planning and prevention.

Figure 1.8: Sea voyage of marine structures key activities.

Therefore, are several modalities that can be presented for the transportation of marine structures. The different modalities with sub-modalities that must be taken into account when selecting a type of transportation or towage are described below.

The approach aims toward the transport of wind towers but several examples are given with other types of structures. Note that one modality is not exclusive of the other, the combination of the different modalities gives the generation of the total design and the selection of the mode of transportation.

Structure definition

When talking about an offshore structure, it must be in mind that it consists of 3 main elements: the substructure, the superstructure and in most cases a mooring system independent of the substructure. This must be taken into account in the sense that in some cases these elements could be a single element as in a FPSO or go previously assembled, however, most of the cases the transportation of each of these elements is different and involves different parts of the project.

As in the case of an oil platform where the TLP substructure is transported independently of the tendons and independent of the housing module.

Superstructure The superstructure is the reason of being of the offshore structure, being that in this section it is in which the main work is carried out. This section includes what is the process plant, the burner, the housing module, the drilling deck or the wind turbine.

Substructure The substructure is the base that will support the superstructure and is the one that has to support most of the forces of the environment, with the waves, the wind and the current, at the same time as the forces of the anchorage system. They can be divided into two categories, fixed and floating.

Fixed Fixed structures refer to those that are in direct contact with the seabed. Fixed bottom foundations can be: monopile, jacket, tripod, gravity-based or suction bucket. Below are the different types of fixed base for wind towers.

The monopile structure is the most commonly used since it is the simplest and in general can be said to be more economical, however, it can only be used for shallow water (about 30 meters deep). The jacket-type structure can be used for depths of around 60 meters, so the construction of it, as well as its installation tends to be more expensive. Below, an image where in summary you can see the different types of foundation with fixed bottom, as well as its advantages and disadvantages.

Floating Wind turbines that have a floating type foundation being used and designed to be located in places where the depths are greater than 60 meters. This is because the cost of a fixed foundation is expensive to be profitable at sea depths above mentioned.
The main types of floating substructures are: New generation TLP, conventional TLP, Semi-submersible, Truss-Spar, MinDOC, Classic Spar, Cell Spar, monobuoy or boat type.

Offshore Foundations Systems In most cases and in particular more in the case of floating substructures, various anchoring systems are used to keep the structure in place.

Piles The piles are steel tubes that are buried in the seabed with which the structure is supported and anchored to the fixed platforms that do not have their own anchoring system. It can be seen for example used to hold a monopile or jacket. It is the most used system to date for its simple design.

Mooring lines The anchoring lines or system of scattered lines consists of multiple moorings that are connected to the platform and the seabed by anchors. In the platforms that present certain geometric symmetry, such as the semi-submersible or the Spar, the dispersion of the moorings can be done symmetrically or grouped around the perimeter of the structure.

Multiple lines are placed in each direction in the case of the loss of breakage of any of the anchoring lines. Depending on how the funding lines are established, the systems can be classified into catenary systems, taut mooring systems or semi-taut lines. In the catenary system with lines composed of chain and rope sections, it is the most used system in shallow waters. At the bottom of the sea the mooring line is horizontal and, consequently, it is only subjected to horizontal forces. It should be noted that the mooring line has to be quite longer than the depth of the water.

This increase in the length of the mooring line also increases its weight and therefore has to be considered at the time of the design of the substructure and the calculation of the flotation forces. As the water depth increases, the weight of the catenary line also increases making the system economically unfeasible. For this, the system of tensioned lines is used, which uses tense synthetic cords, in which the anchor line enters the seabed at an angle of 30 to 45 degrees. It has the advantage that the weight of the line is much lower due to both the density of the material and the smaller length of line used. Tensioned line systems must be able to withstand both vertical and horizontal forces. Finally, the system of semi-tensioned lines is a combination of both systems in which both tensioned lines and catenary lines are used.

Tendons The TLP type platforms have a specific anchoring system which uses a system of vertically arranged steel tubes which are tensioned by hydraulic cylinders housed in the columns of the platform.
Due to the excessive buoyancy of the shell, the movement of heave is limited. The tendons are anchored to the sea floor by means of piles, concrete plinths or suction buckets.

Suction bucket A system formed by a cylinder closed at one end with several valves. The great advantage is that it allows to determine with great accuracy the place where they will be located, which is very useful when working at great depth or when in the area there are several lines and underwater installations.

Recently, suction anchors have become the most widely used method for permanent anchorages in deep water. Another advantage is that they do not need to be hammered like piles. From the ship that carries out the transportation the anchorage is submerged by cranes or ramps, depending on the size of the anchor and it is lowered. Once it is partially embedded in the ground, the valves open to finish embedding and then close again, creating a vacuum in the interior which provides the force to hold the line.

Assembles

Although all the structures are assembled, the location where the assembly takes place is decisive in the cost and time of the project. Pre-assembly of components is an approach applied to limit the duration and, correspondingly, the costs of installation work.

When Pre-assembly is mentioned it is referred to the installation processes and not to the manufacturing processes.

This include in general, (but not limited to):

- Tower segments connection
- Mounting of blades to the hub (“rotor star assembling”)
- Mounting of the hub and two rotor blades (“bunny”) to the rotor nacelle assembly.

This can be seen in the figure 1.9, where different number of assembly are shown.

Full or pre-assemble on-shore By increasing the amount of mounting on land, you can reduce the construction work, being that it is simpler, you can count on more personnel and less expensive equipment, not to mention that the motions produced by the waves are avoided.

However, the partially assembled components reduce the efficiency in the use of the deck space and sometimes increase the number of trips for transport when installing a large wind farm. Also, the weight of the fully assembled turbine requires vessels with large cranes. High lifts, which are more difficult to maneuver and the price is higher. Recently several innovative concepts have been proposed to install the fully assembled tower. Sarkar and Gudmestad (2013) and Phillip M. Schmidt designed the floating substructure concept to transport a fully assembled telescopic structure, and Guachamin Acero et al. (2016) proposed a new concept based on the inverted pendulum principle. As well as several writings on the Windflip concept.

Full or pre-assemble off-shore Another option is to assemble the elements by blocks and full assemble them near the port where there are no large waves and relatively small motions, it is easier to have auxiliary vessels and personnel.

It may be the case to make the complete assembly in these conditions and then be towed to site. Such is the case with Hiwind Scotland.

Offshore assemble in site Most of the offshore wind towers currently installed are assembled on site, carrying the different parts separately on the deck of a vessel; rotor, blades, tower segments and the nacelle. Once in place with the help of a crane, the wind turbine is assembled on the previously installed base, which is usually a monopile type.

This system is being widely used since most of the wind farms are located in shallow waters, so a jackup or liftship with a crane is used, which considerably reduces the motions produced by waves.

Due to the widespread use of the method, experience has allowed several wind towers to be placed in the same vessel at the same time.

The following steps for sea voyage of marine structures are on the next section, since will be a closer approach to WT.

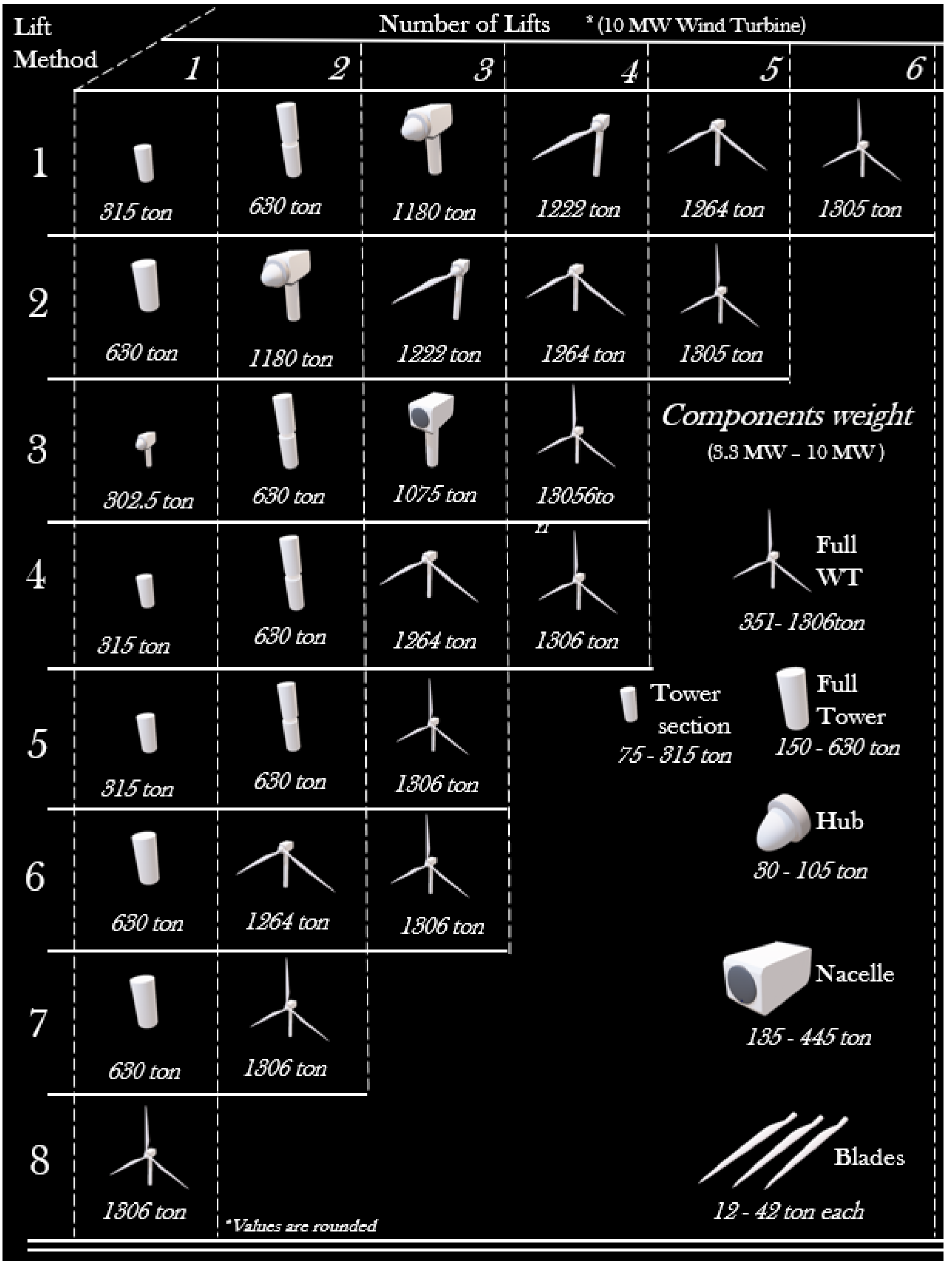


Figure 1.9: Different assembly and lift number configurations.

1.5.5 Transportation of Wind Turbines

The following is directed mainly to the transportation of the wind turbine, since is the main topic for the thesis. Then, from this point it will be referred as wind turbine (WT) only to tower and rotor (including nacelle, hub and blades) unless otherwise is stated.

The transportation of the components of the wind turbine involves several factors which are different from those of the foundations/ substructure, in the sense that several components that comprise it are sensitive and only tolerate a low number of accelerations; "Common industrial practice for designing floating wind turbines is to set an operational limit for the tower-top axial acceleration, normally in the range of 0.2-0.3g, which is typically understood to be related to the safety of turbine components" [**oma**].

The place where the wind turbine are going to be placed affect directly the type and size of wind turbine, is not the same is going to be installed at land or if is going to be installed offshore.

Land Transportation

In order to achieve transportation by sea, first, a large number of transports were made by land. From this, a lot was learned and therefore it can be contrasted the differences between both types and the challenges that this entails.

The main problem with the placement of wind turbines on land is their transportation, since carrying large elements along the roads entails risks for the general population, without having a series of problems that could arise.

Additionally, the size of the assemblies cannot be very large and more in case you have to cross through a town or city with bridges or relatively closed curves. Recalling that there is a significant difference in wind power density as mentioned above.

These problems are not encountered in the installation of wind turbines at sea, but also has advantages in the sense that at the time of installation workers are on stable ground, so they face a lower risk. And therefore the pieces can be welded on site.

Offshore Transportation

The transportation of offshore WT is divided into two main areas: shallow waters and deep waters. This is because there is a big difference between the two. Which will now be explained.

Shallow Waters This case includes zones located up to one hundred meters away from the coast, where it reaches up to sixty meters deep. [8].

In these sites it is possible to install with a fixed bottom and with the help of jack-up or lift-ship vessels, which can be supported on the seabed, allowing the reduction of the movements produced by the waves or wind. This method has been widely used in the majority of the installed outdoor wind turbines. This also allows a greater number of elements to be transported in different vessels at different times and that support for these marine operations is more available.

Another important challenge is to be able to carry the energy, which reaches substations from the WT and from there connects to the ground network.

Deep Waters In contrast to WTs located in shallow waters, the installation of these in deep water remains a major engineering challenge. Starting with the harshest environmental conditions to manage their installation and keep them in position for the operation stage. More intense waves get higher accelerations and therefore a smaller amount of lifts and a faster installation procedure is required.

So far, the only commercial wind farm installed is the one by the company Statoil, now known as Equinor. Their transportation was carried out in two phases. The first was the installation of the WT's, in a place close to the coast, and protected from the wind with the support of a crane vessel, which made the installation of the fully assembled WT in their respective SPAR. From there they were towed to their final destination with the assistance of three OSV for each WT.

By placing them in a fully assembled manner, movements on site are reduced, thus reducing time, leading to a lower risk and the helping the structure to improve its capacity to withstand the marine environment offshore.

Hence the importance of the development of techniques, equipment and boats that allow this to be achieved in the medium term.

Route

An important factor for the analysis and planning of the marine voyage is the route in which it will take place.

It is not the same if it is a trip between two points that are in a protected sea or in the same area that you have to cross several zones and latitudes. The important information that should be obtained for the route are:

Route length, statistics of the zones such as wave periods, significant waves, wind average speed and meteorological conditions for short-term and by seasons. The specific data for the selected route for the study of this thesis will be described in a following chapter.

Type of voyage

In general, the marine transport operation of the structure can be classified in two: Dry transport or towage.

Transportation Refers when the structure is on the vessel with self propulsion.

Dry Towage Means that the structure is not in direct contact with water. It can go on a barge or on the deck of a jack up (without self propulsion) that is being towed.

Wet Towage Is when the structure is on the water, using its own buoyant force during the travel. This can be as much by the placement of caps or floats as it usually happens with the jackets once in place. Or that the structure has its own flotation system such as an SPAR or FPSO without self propulsion. As the case of the last stage of the voyage for the Hywind Scotland Wind Turbines, which were taken from the final assembly site floating with its substructure to the site where the wind farm was installed.

Vessels selection

The following is determined with respect to the type of vessel and the configuration of the number of vessels. A different combination for different structures to be transported or towaged can benefit the speed and cost of the entire process.

Type of Vessels configuration The following vessels are those that normally participate in the process of transportation and installation of marine structures.

- Offshore support vessel
- Jack-up
- Lift Ship
- Crane vessel
- Barge
- Tug

Number of vessels configuration One ship configuration. As an example, a lift-boat with crane that can transport and unload structures on its own.

Two ship configuration. In which is the case of the boat that transports during the route and a crane that makes small transportation on site, or the case of the tugboat that carries a Jack up.

Multiple ship configuration, when the structure is larger and multiple tugs are required, the barge or boat where the crane ships are transported.

In general, the more ships used, the more expensive and complicated to maneuver, but can be the case that a very high specialized vessel tend to be costly, but efficient.

Also, is need to take in consideration that all requirements from the transport vessels (including tug power, arrangement of vessels, navigation equipment etc.), as its documentation should be obtained for each ship.

1.5.6 Catamaran Vessels

Overview

As has been stated above the selection of the ship can produce a more efficient or safer transportation since is a balance of needs, you can gain stability or capacity but in return, your resistance also increases, then your fuel consumption. The selection of a catamaran vessel can be a good selection for the intend of transportation of wind turbines since it has important advantages that can benefit the project. [11][18]

Before commenting on the catamaran type itself and its advantages and disadvantages some definitions should be done for an easier understanding.

A catamaran vessel is a ship which hull is composed of three main parts, two of them meant for the buoyancy and stability and a third one that connects this two parts. If the buoyant parts are symmetric they are denominated Amas, Demihulls or Pontoons; in the case that they are not symmetric, the ”main ama” that provides the most of its buoyancy is denominated Vaka. The section that works as a joint of the two amas or between the vaka and the ama is the Aka, the Cross Deck or Cross Section. For the next chapters, since the vessel for the study is symmetric to the centre line, the selection of the terms amas and cross deck will be used.

Advantages

Stability and hi center of gravity; Some features that the catamaran type has is that the waterplane area for each ama is in some degree apart from the center line, this producing that its inertia or with other words the second moment of the area increase, in comparison with a mono-hull that have the same waterplane area. Since there is two elements that are most important to grab a general understanding for stability, being one the inertia of the waterplane (Iw) and the other the displaced volume. In one word the stability is correlated to the metacentric height, GM; but this one is determined by the two elements mentioned before with the next relationship:

$$GM = KB + BM - KG \tag{1.1}$$

Where;

$$BM = \frac{Iw}{\nabla} \tag{1.2}$$

Light dead-weight; If the main idea of the ship is to carry lot of cargo inside, a mono-hull is better idea since the space inside the ship is used for storage, but when light cargo is to be on board, the need of more ballast or less displacement is needed, since caring more ballast is not the more efficient process, getting less displacement with the use of a catamaran vessel is a good option.

Deck area; Even, in relationship with the light dead-weight, if the cargo is needed to be on deck, catamaran ships present the chance to have a large deck area to place structures and equipment's.

Disadvantages

Propulsion system

The main problem with the propulsion system is that, from medium to large multihull vessels, is needed to have double of everything at machinery. Is more expensive to have two engines giving the same power as just one, and the same happens with all the auxiliary machinery.

Construction challenges

The less experience that exist in compare to monohull, the need of perfect symmetry of the amas, complex cross deck structure and the double machinery space as stated above make that a catamaran vessel present a bigger challenge at the time of construction.

Features that need to be think twice

There are some specifications that can be an advantage or a disadvantage depending the needs and the navigational space.

Draft; Since, smaller displacement is needed the draft can be reduced. But in the other hand the stability of catamaran ships is mainly related to the draft of the amas. On a monohull the GZ curve starts to decrease when the water reach the deck level, but for the catamaran case it happens when one of the amas leave the water. This is going to be shown in the procedure chapter.

Beam; The higher distance between the amas the better transverse stability the vessel will have, this produce wide ships that can be restricted for navigation in narrow channels but can be quite good at wide channels or at open sea.

Resistance Is another specific value that can change depending the specifications. If a vessel need to be fast, slender amas reduce the wave resistance. If the division of a monohull displacement is given into two amas, then the wet surface increase, therefore the frictional resistance increase, and this one is the most important one for slow-moderate speed. For the specific case of wide monohull or barges then the wet surface will be bigger even being monohull, then the last statement does not fit, but this type of vessels are meant for improve stability and not as much for resistance.

Criteria with legal framework; There is a general problem with criteria for catamaran ships, there are no criteria for long slow catamaran vessels. The general intact stability criteria ask for a max GM above 25, that most of the of multi-hull ships can not accomplish, then part B of the code need to be seen, where a good criteria to follow can be the offshore supply vessels for max GM below 25 can be used for ships with length less than 100m. Another option is if the catamaran fit for the High Speed Vessels code, then there are specific criteria for multi-hull vessel to be used. Then as is stated in part B, using the general criteria from part A of the IS code as basis with some additional specific criteria from part B should be done in agreement with the maritime authority or society class.

1.5.7 Analysis and Planing

When the transportation of a marine structure is going to be planned the following general considerations should be considered.

- Proof of structural integrity of the asset and the components in all the stages.
- Lifting points strength.
- Limiting values (lifting speed, environmental conditions restrictions, allowable duration, etc.).
- Sufficient load bearing capacity of the pre-assembly sections.
- Dimensions, weight, and location of centre of gravity of all important / key components.
- Environmental conditions values (wind, waves, current).
- Transport loads and sensibility to weather changes

Transportation Analysis

Marine operations, including transport, falls on the analysis of the different elements to seek the safety and efficiency of the process. The forms of the vessel and the structure, the properties of the material and the procedures to operate are examples of some of these elements.

From the perspective of this project, the elements analyzed are supported by stability, motion and structural analysis. The theory explained in the following chapter and used to solve the objective of the work is based mainly on the texts;

- O.M. Faltinsen, Sea Loads on Ship and Offshore structures;[9]
- Jensen, Load and Global Response of Ships;[15]
- Ulrik Dam Nielsen, Ship Operations -Engineering Analyses and Guidance; and,[19]
- Marilena Greco, Sea Loads - Lecture Notes. [10]

Securing devices

The following subsection describes the different systems that are used as sea-fastenings for the transportation of marine structures. The selection of a type or a mixture of several of the types of sea-fastening presented will correspond to the shape, size, type and complexity of the structure.

Welded plates This type of fastening consists of welding plates and tubular sections of the vessel's deck directly to the structure being transported or to the transportation frame.

The plates welded as marine insurances are the most used system in the offshore industry, since this system can be easily coupled to any marine structure, providing a great rigidity for the transportation stage, besides that it is an economic system. As is the case with wind turbines, this method is not used directly in the tower for various reasons such as reducing the corrosion that the tower acquires or inducing deformation loads among others.

Transportation frames It consists of the placement of temporary structures that give support to the structure. It is generally used as an interface between the deck and the structure or a system that dampens or applies force. Therefore, more aggressive methods can be applied to this structure as they can be welded directly to the boat and while these frames are provided with some kind of system that helps to firmly hold the structure to be transported without damaging it.

Bolts Since it is not possible to weld the wind towers on site (offshore), the different sections of the wind turbine have holes that are used to assemble the wind turbine, joining the different sections with bolts. So, the same holes are used to hold the sections for both transport and lifting.

This method consists of the placement of transportation frames that are welded to the deck of the boat, where the various sections of the wind turbine are fixed with the bolts.

Both for ground transportation and the offshore transportation of wind turbines, the Bolts system is being widely used for the facilities provided by the system. The assurance that the sections have sufficient strength in the section where the bolts are placed; The possibility of having a variety of different providers in different parts of the world; Standardized and regulated procedures as in "E.2 Bolted connections" [5] and; The ease of checking easily by the technician if they are well placed reducing the risk of accidents.

The drawback of the system is that you need a lot of bolts, so you need more staff and it takes time to remove more than 300 bolts per section. Additionally, these cannot be reused several times as a rule.

Lashing wires and tensioners This method consists in placing a variety of tensioners in different directions since they only work under tension, placed from the structure or braces placed in the structure to the transport frame or to the deck of the vessel. In this way, in addition to the structure being fixed, the movements of the structure are limited. In general, it is a method little used in offshore transports since the movements of the boat deform and fatigue the cables so a system for re-tensioning and damping has to be coupled.

Jacks A jack is a device that apply force by a screw or by hydraulic power perpendicular to the area. This device should get fix to the transportation frame or to the ship deck to compensate. Tis method is normally used by fitting several number of this devices with different positions since only work in compression and can be used in the wind turbine in almost every part of the tower.

Wedge shaped clamps A wedge-shaped clamp is a system in which the wedge is hydraulically pressed on the flange or base of the structure. Because the clamp must compensate for the thrust, it must be attached to a support frame. This method could be an option in the fastening of wind turbines, if the clamping frame is designed so that the wedges are inside the structure, since a support point does not protrude from it. The main advantage of this system is the speed with which it acts, but in case of failure it is more difficult to change it at that moment.

Rotating clamps Most commonly used in fastening anchor lines, and known as shark jaws, this type of jaw rotates on a shaft supported on the deck of the vessel or on the support frame. For a series of systematized works can be very useful for the high speed and high strength that can support this type of jaw. The disadvantage is that it is not easily adjustable to different positions, so if the wind turbine has a different shape or a different diameter in the base this system could not be used.

Rotating wedges This type of wedges rotates to support the base of the structure. Its axis is perpendicular to the plane of the roof and its shape allows the structure to be adjusted with the necessary force. But it is a system that is prone to vibrations.

Integration in the ship structure By integration is meant to refers not only of direct welding of the structure to the deck, means that some parts of the structure are inserted in the vessel. In the case of a wind turbine tower if part of it is introduced in the vessel can help to maintain a lower CG and to add support in different sections.

Mechatronic Devices In this subsection refers a method or a combination of methods that where already mentioned using electronics in it to control the force and the motions of the device. Just as in electronic winches, rotating clamps or more complex supporting structures as the gripper developed by Ulstein.[25]

Planning and prevention

Finally, a series of elements that could be considered a little obvious but which are of great importance since they are related to planning and prevention are mentioned below.

Planning of transport within a wind power plant project shall incorporate the risk management process, with the target to ensure during TI the transfer of assets and components from one defined safe state to another, reducing in each phase the potential hazards as it can be seen in fig 2.1.

Planning:

- Preparation of all Offshore transport documentation for the different authorities, as well as for different machinery operators.
- Expected route and duration of maritime transport.
- Selection of a period of the year that is suitable for transport, taking into account the climatic conditions (storms, time window, ice, tides, wind speed, significant wave heights, changes in the level of water induced by the wind, variations of the tide, speed and direction of currents. etc.).
- The chronogram of the project.
- Availability of access to the transported structures.

By ”Nearshore transport”, it mean transport by water through continental waters and on the sea near the coast.

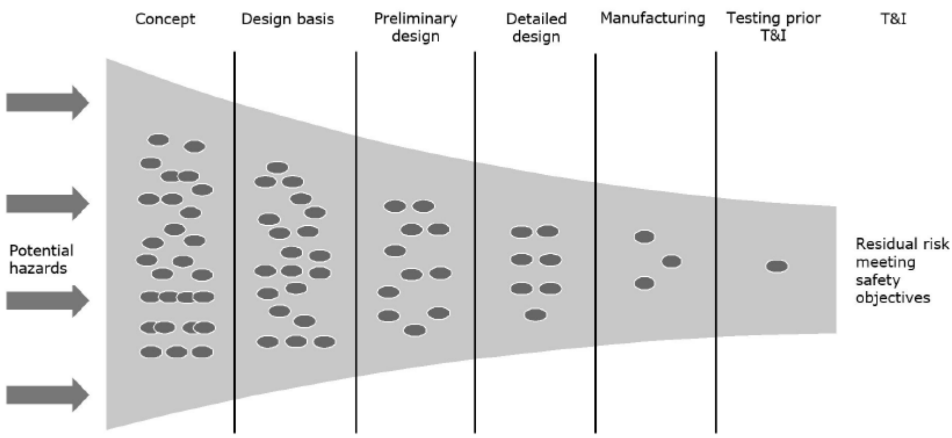


Figure 1.10: Achievement of the safety objectives.

Prevention:

- Sufficient area of work and maneuver y absence of obstacles for all movements in the horizontal and vertical directions, as availability of area to rotate, possibility of navigation in narrow waterways or transport Nearshore, obstructions (bridges, depths, cables, transit of other vessels).

- Condition of the acceptable surface (clean, purity, flat, dry, necessary drainage, oil, etc.).
- Supervision of systems and documentation update.
- Exhaust plan and emergency plan.
- Availability of suitable lifting devices for personnel, equipment and tools.
- Availability of protective measures required for the structure and components (wood paneling, heaters, fire protection).
- Supervision of the general conditions and in specific areas as well as elements of the structure, such as temperature, humidity and tensions.
- Lighting and sufficient distribution of light.
- Water for consumption, compressed air, electricity supply and other consumption's.
- Availability of personal protective equipment (PPE).
- Routine inspection programs, as well as procedures and checklists.
- Qualification and certification of personnel.

1.5.8 Rules and Guidelines

In general, the application of rules and standards can be considered confusing at first instance, since they cover a large number of activities and areas. The main issue is to be able to distinguish in general which "rules" exist, and which are those that apply to meet the security objectives. By mentioning "rules" for this report, in a generic way and not to a specific one, it will be understood as the set of rules, norms, standards, guides and recommended practices.

The safety objectives are the criteria indicated in the "rules" that must be met to ensure the safe execution of marine operations, in particular for the transport of fully armed wind turbines. These security objectives can be quantified by key elements such as:

- Personnel health and safety risk
- Financial losses, among others due to disturbances of the time-line, damage or losses
- Impact on the environment.

There are mainly two types of "rules". Those issued by the International Maritime Organization (IMO) through the government of each country, which in general are mandatory.

For the case of this report the main rule from IMO to follow will be the "RESOLUTION MSC.267(85), adopted on 4 December 2008,ADOPTION OF THE INTERNATIONAL CODE ON INTACT STABILITY, 2008" known as the 2008 IS code.

And those issued by companies, which at the beginning are not mandatory since one can select between different companies and different services that these provide such as class societies or standards issued by the international standardization organization (ISO). Although it is not mandatory to choose to adhere to one or more of these ”rules”, it provides several benefits that help to more efficiently meet the company’s security objectives, such as having the possibility of being covered by insurance. Once you have chosen to follow the ”rules” of any of these companies is when they become mandatory, and when compliance are issued certificates of compliance, so their ”rules” have to be followed to continue having the benefits and stay certified .

The approach is directly to that issued by the class DNV-GL. The ”rules” issued by DNV-GL, are classified into three groups;

- Maritime;
- Energy; and,
- Oil and Gas.

And although they cover different areas, since they are developed in the same environment and are closely related there is a relationship between them in the way that the ”rules” of one of the areas refer to, and request to, follow what is established in another area. Sometimes, in the case of an oil rig, it is requested to see what is described in the maritime, or in the case of a wind turbine, it is requested to see something described in Oil and Gas, which in some occasions could cause confusion, but it is a way for them to be written once and that the established information is not disperse, which avoids possible errors in case of modifications. For the next sections the different “rules” of the different areas has been extracted and resumed with the objective to create a first approach of its application and to determine the sections that have particular scope for the catamaran wind turbine installation vessel.

Energy

The Energy area meets three categories;

- Service specifications (SE),
- Standards (ST),
- Recommended practice (RT)

The SE define the relationship between the company and the client, the legal and liability criteria and the certification procedures. The ST is where the criteria and technical requirements that must be fulfilled meet. PRs, although they are not obligatory, are the way to confirm that the choice of a particular method is carried out in the best possible way. As an example of the latter, it is not mandatory to use a finite element software for the calculations of some marine operation, but if it is used, in the RP there are parameters that helps to know if the model is reliable.

In the case of the transportation of wind turbines, there is within this area the standard DNVGL-ST-0054, ”Transport and installation of wind power plants” which provides the requirements to guarantee the structural integrity of wind turbines, substructures and other components that are part of a wind farm.

Transport and installation of wind power plants The standard includes requirements for the planning of T I, requirements for the execution of T I, requirements for evaluations and verifications once T I is finished. Therefore, what is relevant in this standard is what has been described previously in the chapter 3.

Additionally, it mentions that the design and analysis of the transport stage should be done according to the following Standards, For:

- support structures for wind turbines: DNVGL-ST-0126.
- other offshore steel structures: DNVGL-OS-C101,”Design of offshore steel structures, general - LRFD method”.
- nacelle and hub of wind turbines: DNVGL-ST-0361, ”Machinery for wind turbines”.
- rotor blades of wind turbines: DNVGL-ST-0376.
- offshore substations: DNVGL-ST-0145.
- During the development phase motion criteria may be applied according to DNVGL-ST-N001 Sec.11.
- verification of motion influences during offshore transport, loads for the relevant environmental conditions shall be determined by motion analysis, DNVGL-ST-N001.
- Also is important to add, DNVGL-ST-0437 Loads and site conditions for wind turbines, which is not mention in ST-0054.

It need to be noticed that in general the rules and requirements for structural strength analysis are mostly related to steel structures, therefore, for structures built of other materials, adequate safety levels shall be achieved using other standards.

Finally, this is part of the requirements for certification, but does not indicate what the requirements for certification are. As the norm does not cover the design and manufacture of: vessels for T I, sea lifting and fixing devices.

Oil and Gas

Since Oil and Gas have been developed first and most of marine structures installations at sea knowledge is from this area, the rules are more developed for it than for wind offshore structures. Therefore, in many of the rules of design of steel structures at sea will be referred to it.

In the case of Oil and Gas ”rules” will be refered just to DNVGL-ST-N001 ”Marine operations and marine warranty”, therefore next sections can be find in it with more detail.

Sea voyages For sea voyage, it is meant the transportation on deck or tow of the structure in dry or wet as explained the above. If it is intend to perform a complete sea voyage planning and analysis, the next points should be taken into account.

- Motion response
- Design and strength
- Floating stability
- Transport tug selection
- Towing equipment
- Voyage planning
- Pumping and anchoring equipment
- Manning
- Multiple tows
- Additional requirements for specific asset types.
- Information required for MWS approval.

1.6 Structure of the Msc thesis

The Msc thesis report is structured as follows:

Ch.1 Introduces the report starting by its objective and motivation. Presenting the energy and wind industry as background for this stud, followed by literature review of wind turbines transportation and stability, motion and structural analysis of vessels during transportation.

Ch. 2 Presents the flow chart on how to reach the objective and the theory behind most of the steps; particularly for the dynamic response analysis.

Ch. 3 Contains a step by step of the procedure followed for the analysis. Introducing the wind turbines selected, the vessel particulars, and the route environmental loads that were used. Following are the key aspects about the modelling of the FEM models.

Ch. 4 Then, the design applied for stability and dynamic response analysis are given. Closing with the steps of the post-processing of the results in order to obtain the most probable maximums MPM of displacements, velocities and accelerations for specific points of interest.

Ch. 5 The results for each part are presented; improved design, transportation analyses and sea-fastening structure results.

Ch. 6 Discussion of the mentioned above results.

Ch. 7 Conclusion and recommendations for future work are presented.

Chapter 2

Methodology

2.1 Scope

In the following chapter the flow chart with each step of the method followed to achieve the objective is presented. It covers four important parts that are the improvement of the model by iterations, quality check of the mesh, some stability and dynamic analysis performed on ”box shape” vessels to reinforce and prove the theory on catamaran vessels, which is not as developed as mono-hulls. Followed by the theory that covers some of the calculations done to follow it and to satisfy the objective of the present thesis.

2.2 Method

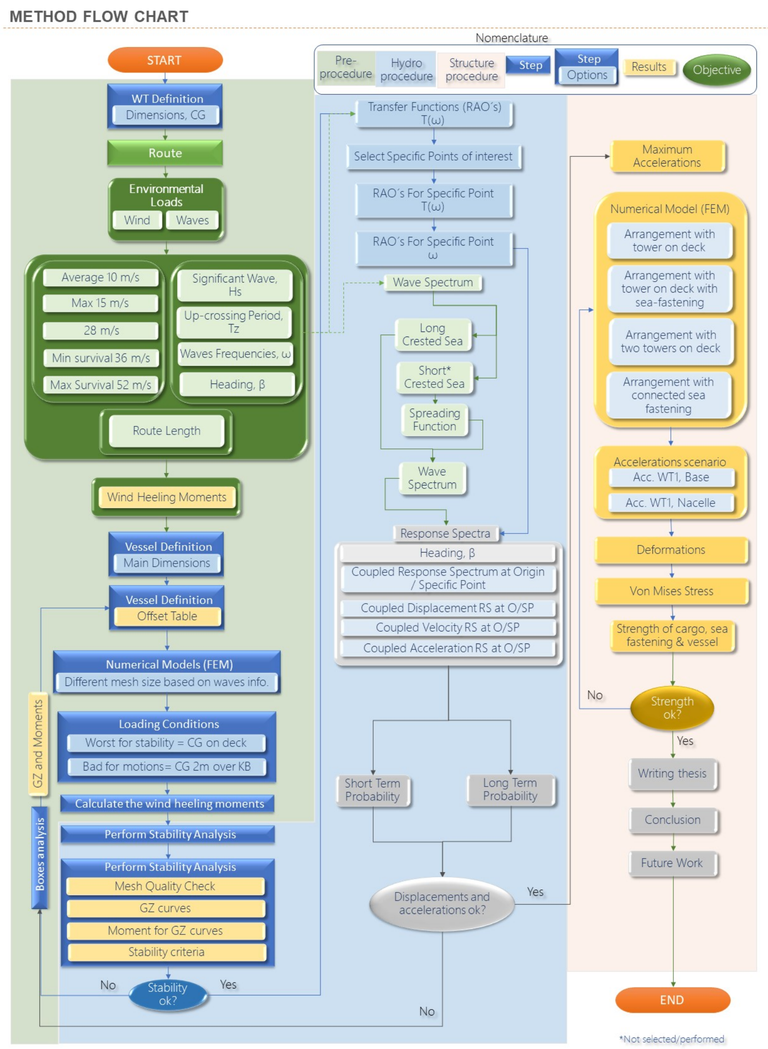


Figure 2.1: Method followed to perform the objective.

The flow chart is divided into three main parts. The first part corresponds to the pre-procedure that was carried out in order to improve the form and the results obtained from the vessel, being that when generating the numerical model several parameters have to be considered as input data such as the particularities of the structure, which in this case are the four fully armed wind turbines; the particulars of the boat, as well as the meshing of the same, the different models that are required to perform, the guide points for a reliable quality meshing; the definition of the route with which the charges will be determined. In addition to this, the analysis was carried out on the ”boats in the shape of a box”, more specific on the side of the simplified comparison of the stability of these and even a less detailed analysis of the RAO of these, together with the values involved to satisfy the dynamic equilibrium equation.

The second part is the one that corresponds to the hydrodynamic analysis including the stability and motions of the boat, which is the central part of the work. It describes the steps taken along with some of the alternatives and decisions that must be taken when displaying the results.

And finally, the steps that are followed to perform the structural analysis of sea-fastenings are indicated. In general, it is a way in which, in a simplified way, the method to be followed is expressed in order to carry out the different parts of the report.

2.3 Theoretical basis for design improvement

2.3.1 Numerical Models

Mesh Quality Check

In order to determine the meshing of our model in an initial stage, there are two methods. The first is to follow the recommendation of DNV-GL to place eight panels for each wavelength which would be the correct one in case a more detailed hydrodynamic-structural analysis is required, in the case of this report the second recommendation will be followed which is the one found in the GENIE software manual of SESAM, which specifies that at least 4 panels will have to be used per wavelength. This is understood since the system requires two points for the period in up-crossing and at least one crest and valley to represent the elevation of the wave. Therefore, a finer mesh allows analyzing higher frequencies. Very high frequencies create a second response peak and therefore, at a more advanced stage of design it is important to analyze it, as expressed in Nielsen, 2010 [19]. In this stage and since the entire structure of the vessel is not yet defined with an average mesh in which the criterion of the 4 panels is met, it is predicted that it will be sufficient, same that it checks with the following quality check. 6 different mesh types were used, with different configurations to perform a quality check of the data. Meshing corresponds to Very Coarse, Coarse, Medium, Fine, Very fine and combination. The results are shown in the next chapter.

2.4 Theoretical basis for hydro-static and hydrodynamic analyses

2.4.1 Assumptions, constants and Notes

- Good weather during transportation.
- Potential flow
- Linear theory
- Gravity of 9.80665 m/s^2
- Uniform depth of 300m
- Water density 1025 kg/m^3
- Infinity borders (no coastal interference)
- Zero forward speed can be assumed. Slow fwd. speed due to transportation arrangement can be use if necessary
- The project will follow the relevant IMO and DNV standards
- The general dimensions of the vessel will be established in collaboration with the advisor
- HydroD software will be used

2.4.2 Vessel Dynamic Response

For centuries scientists have worked and studied to generate mathematical models and formulas that described the events that happen in nature. The case for the bodies that are or not in movement and the forces to which they are subject has been pillars of the investigation with Newton and D'Alambert among others.

The ships that are in the sea, although they suffer deformations and deflections, for the general practical cases they can be considered like rigid bodies that interact with the forces of the environment. The relationship that a rigid body has in relation to the waves will then have to comply with the equation of dynamic equilibrium:

$$Fi + Fd + Fs + P(t) = 0 \tag{2.1}$$

So the sum of the time-dependent external forces (P (t)), the force of inertia (Fi = -m$\ddot{u}$), the damping force (Fd = -k$\dot{u}$) and the restoring force or rigidity of the system (Fs) = -ku) will have to be equal to zero; being m the mass of it, c its damping and k its stiffness, multiplied by the acceleration, speed and position of the body as a function of time respectively.

Then, by rearranging the above equation can be presented as follows:

$$P(t) = m\ddot{u}(t) + c\dot{u}(t) + ku(t) \tag{2.2}$$

The forces and moments derived from the previous equation, in the case of vessels, are referred to as hydrodynamic charges, which can be divided into two parts.

The first part is the one that expresses the forces and moments that the waves generated by the body without it changing its position. These hydrodynamic forces are called wave excitation loads, which in turn can be subdivided into the energy contained in the movement itself of the waves and the charge generated by the diffraction of the waves when meeting the body. These can be calculated by Froude-Kriloff, the strip theory and the approximation by long wave respectively.

$$F_{ext} = F_{fk} + F_d \tag{2.3}$$

The second part involves the forces and moments in the body when it is forced to oscillate at the frequency of excitation of the wave, generating hydrodynamic charges such as the added mass, the damping force and the restoring force, as it had been previously mentioned.

Which is easier to solve if a potential flow is assumed:

$$V = \nabla * \phi \tag{2.4}$$

V being the velocity, the gradient ”Del” and ϕ the potential function. For what is an irrotational ($\nabla \times$ V = $\nabla \times \nabla\phi$; $\nabla \times$ V = 0, since curl of gradient is always zero), incompressible (∇.V = 0; $\nabla^2\phi$ = 0 known as Laplace equation) fluid.

In a very general way, if the different flows satisfy the Laplace equation, they can be added directly to obtain the complete movement of the flow around the vessel which acts as a boundary layer rather than as a body. And so, following the linear theory. In addition, with the concept of superposition, we can integrate several types of waves with different periods and amplitudes, to generate an irregular wave.

From these assumptions for the forces and moments, applied and resulting in the body, can be obtained the movement that the body will present as a function of time.

Determining the position of a body with one or a few degrees of freedom over a given space does not cause great conflicts, but a boat can move in six degrees of freedom, these three movements of translation and 3 rotation movements applied on the origin of the body. For this reason, three different conventions for reference axes have been agreed upon.

The first corresponds only to the axes on the boat depending on the same, finding longitudinally ”surge”, laterally ”sway” and vertically ”heave”; and in rotation, turning on the longitudinal axis ”roll”, turning on the lateral axis ”pitch” and turn on the vertical axis

”yaw”.

The second corresponds to the space in which the boat is navigating, so the x-axis coincides with the longitudinal axis of the boat, in addition to the sum of the movements and turns along and on the respective axes produces movement and location of a point of the body, at the origin ”x”, ”y” and ”z”.

Finally, the axis of fixed coordinates, X0, Y0 and Z0, with which reference is made to the direction in which the vessel is navigating and also reference to the direction of the swell, as well as other environmental factors.

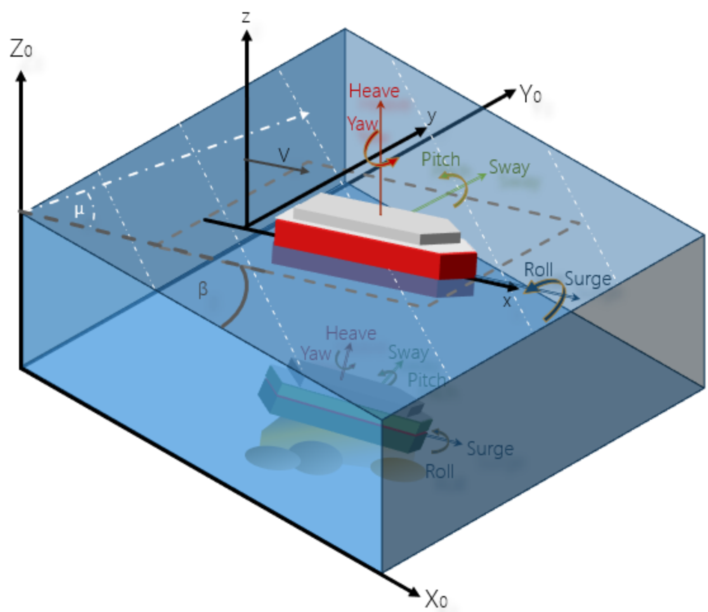


Figure 2.2: Different coordinate Axis

Bearing in mind the above, and taking the first-mentioned reference system, one can calculate the forces on the body.

For this reason, taking as an example the forces in Heave and as derived from M. Greco, 2012 taking as an example the exercise 3.1 of Faltinsen, 1990, where it is applied for a ”box shaped vessel”, can be represented as follows :

$$F_{ext,3} = F_{fk,3} + F_{d,3} \tag{2.5}$$

$$F_{ext,3} = \rho * g * \zeta * B * L * sin(\omega t) \tag{2.6}$$

Later, solving the equation of the movement these forces are used to obtain the motion, where taking the previous example, where it is not contemplated damping nor coupling:

$$\eta_3 = \frac{F_{ext,3} sin(\omega t)}{[-\omega^2(m + A_{33}) + C_{33}]} \tag{2.7}$$

The above formulas represent the motion the vessel would have for certain types of waves with a specific frequency. Knowing how the vessel reacts or moves for different types of wave frequency, the RAO of the vessel can be drawn.

These movements and forces can be measured experimentally in a test tank, which is expensive for preliminary designs, or through mathematical models.

For a numerical model, they can be expressed for an approximation based on a time domain or an approximation based on a frequency domain. For the approximation based on time, the model is made, and the movements are analyzed in a certain amount of time.

Using the frequency domain approximation, the displacements, speeds and accelerations mentioned can be calculated from data and generated statistical formulas to know globally how the movement of the ship will be represented, considering the probability given by the spectrum of the response.

If the movement of the ship in the open sea wants to be known, different linear waves with different wave frequencies, or modes, with the corresponding magnitudes must be added to generate the desired wave type to obtain the response spectrum of the ship.

To obtain this response spectrum requires two elements, the wave spectrum (Sω) and a function that serves as an intermediary between the response of the ship and the wave spectrum, this function is known as the transfer function, response amplitude operator, RAO or variable response (Hω).

The above is described by the following equation:

$$S_R(\omega) = S_\zeta(\omega)|H(\omega)|^2 \tag{2.8}$$

For the first term of the right side of the equation, Sω different formulas have been developed for wave spectra such as the wave spectrum of Pierson Moskowitz or the spectrum of JONSWAP among others. Which relate different parameters such as the significant wave (Hs) or the up-crossing period (Tz) and the wave frequency (omega) to determine the magnitude of the irregular wave type.

For the case of this work, and in agreement with the supervisors, a PM wave spectrum was used for which the following formula was used:

$$S_\zeta(\omega, Hs, Tz) = (A\omega^{-5})exp(-B\omega^{-4}); \tag{2.9}$$

Where:

$$A = \frac{Hs^2}{4\pi}\left(\frac{2\pi}{Tz}\right)^4; \tag{2.10}$$

$$B = \frac{1}{\pi}\left(\frac{2\pi}{Tz}\right)^4; \tag{2.11}$$

Additionally to this, the wave spectrum can be modified by the decision of taking short crested sea instead of the long crested sea. The long crested sea, also known as two dimension waves is the full wave spectrum as stated above or as it can be seen in the image of the PM spectrum for Hs of 3 meters and Tz of 9 seconds, where all the energy of the wave is only related to one direction. Obtaining all the waves in the same direction is unrealistic since at open sea waves come from very different directions creating an even more irregular response. On the other hand, by the application of the long crested sea, the motions will be bigger and therefore is prove to be a more conservative analysis. For the

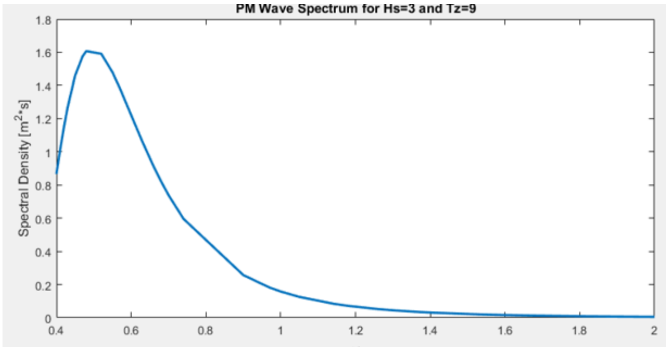


Figure 2.3: PM spectrum

case of the short crested sea, or three dimension waves, the spectrum for each heading is multiply by a spreading function and then added together in the way that the energy dissipates for different directions. The function for different S values is shown, in this case is limited to 90 degrees to each side of the main wave direction. It is normally used a S value of 1, therefore the cosine value has an exponent of 2, this (at can be seen in the figure 2.4) this produce that the main wave direction and the most lateral direction does not have as much difference as using a big S value where most of the energy is applied from the main direction. The second term is obtained, as mentioned above, using the forces, moments and motions for different wave frequencies, for which different software can be then used to obtain the RAO in an immediate way and for complex vessel forms.

If the velocities or accelerations want to obtain at a said specified point, then the first or second derivative of the motion will have to be contemplated, with which the formula of Sr(ω) changes to be:

$$\dot{S}r = S_\zeta(\omega)\omega|H(\omega)|^2 \tag{2.12}$$

and

$$\ddot{S}r = S_\zeta(\omega)\omega^2|H(\omega)|^2 \tag{2.13}$$

To analyze a specific point of the vessel in space. For example, and in relation to the vessel of the present work, to analyze a point in the base of the wind turbine tower or the

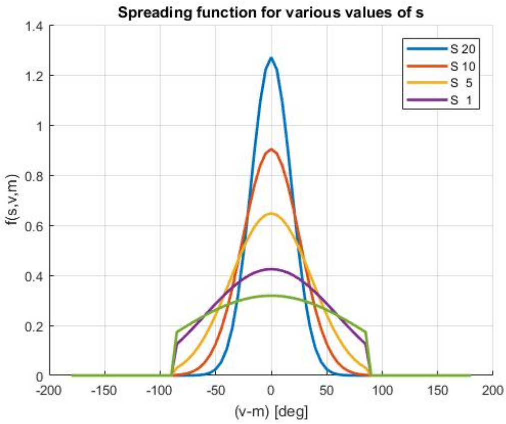


Figure 2.4: Spreading function in relation to S value

accelerations in the center of gravity of the nacelle, which are of importance and interest to achieve a successful transport, a series of coupled RAO's are meant to be used.

The motion at any point $P(p_x, p_y, p_z)$ of the rigid body, for coupled movements, can be represented by the following equation:

$$S = (\eta_1 + z\eta_5 - y\eta_6)i + (\eta_2 - z\eta_4 + x\eta_6)j + (\eta_3 + y\eta_4 - x\eta_5)k \tag{2.14}$$

Where i, j and k are unit vectors.

Another way of expressing it is by indicating with complex numbers and trigonometrically the amount of movement that the boat has on an axis x, y or z, when coupling the translations and rotations, then;

On the x axis

$$\Re x = surge + pitch * p_z - yaw * p_y \tag{2.15}$$

$$\Im x = surge + pitch * p_z - yaw * p_y \tag{2.16}$$

On the y axis

$$\Re y = sway - roll * p_z + yaw * p_x \tag{2.17}$$

$$\Im y = sway - roll * p_z + yaw * p_x \tag{2.18}$$

On the z axis

$$\Re z = heave + roll * p_y - pitch * p_x \tag{2.19}$$

$$\Im z = heave + roll * p_y - pitch * p_x \tag{2.20}$$

Then for each one, the Real and Imaginary part are combined to get the magnitude of the RAO and the phase angle (rad).

$$RAO = \sqrt{\Re^2, \Im^2)} \tag{2.21}$$

$$\phi = atan(\frac{\Re}{\Im}) \tag{2.22}$$

In this way, the RAOs are obtained with reference to the X, Y and Z axes, so by applying the above Sr equation, the response spectrum can be obtained.

Additionally, these RAOs will have to be calculated for different angles and thus determine the motion of the vessel if the waves come from different angles.

For the case of the wave spectrum, different spectra will also be obtained for different values of Tz or Hs.

It is important that both the RAO and the wave spectra share the same range of angular wave frequencies in order to relate the magnitudes corresponding to the same frequency.

Short Term statistics can be obtain by the calculation of particular information of each spectrum, in relation to the aforementioned parameters (Tz, Hs, beta, motion, velocity, acceleration, axis; x, y, z).

Example of this are the n moment of the spectrum,

$$m_n = \int_0^\infty \omega^n S_\varsigma(\omega) d\omega \qquad (n = 0, 1, 2, ...) \tag{2.23}$$

where the 0, 1, 2 and 4 moment will be needed;

the variance,

$$\sigma = \sqrt{m_0} \tag{2.24}$$

the mean period of the peaks (different of the spectrum peak period) ,

$$\overline{T_p} = 2\pi \sqrt{\frac{m_2}{m_4}} \tag{2.25}$$

the mean zero crossing period,

$$\overline{T_z} = 2\pi \sqrt{\frac{m_0}{m_2}} \tag{2.26}$$

the number of zero up-crossings, Nz value

$$Nz = \frac{D}{Tz} \tag{2.27}$$

where the D corresponds to the short term seastate duration;

the epsilon value, ε, which is the ratio between the average period of the peaks and the average zero crossing period, where a narrow banded spectrum will correspond a ε value neer to 0, and close to 1 for wide banded spectrum.

$$\varepsilon = \sqrt{1 - \frac{\overline{Tp^2}}{\overline{Tz^2}}} = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \tag{2.28}$$

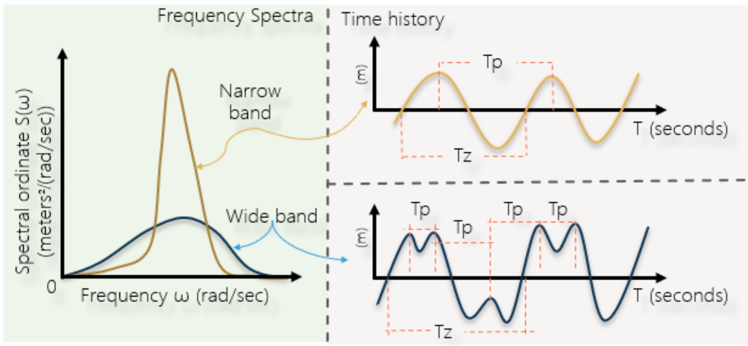


Figure 2.5: Narrow banded and Wide Banded

and most probable maximum (MPM), which is the maximum value expected,

$$MPM = \sqrt{2m_0 ln(Nz)} = \sqrt{2}\sigma\sqrt{ln(Nz)} \tag{2.29}$$

2.5 Theoretical basis for the preliminary design of the sea-fastening structure

Using Sestra and represented in Xtract both of DNV, the global structural analysis is carried out whose objective is to identify the highest concentration of efforts for the different conditions evaluated taken for the maximum accelerations calculated for the hydro-static and hydrodynamic analyzes, which will be performed in greater detail and compared with their ultimate strength for this preliminary design state.

2.5.1 LRDF

The design factor method for load and resistance (LRFD, load and resistance factor design method) is an alternative or supplement of several methods and theories to study structures. This is based on the observation of real structures and analyzing their responses, in order to determine a factor for the resistance as a factor for the loads. This allows us to get closer to the point of flow of the materials but allow us to be sure that it is strong enough to withstand all the loads that could arise at any time, to achieve a safe environment for the staff and to achieve an adequate durability against the passage of the life of the structure.

There are four main design areas to use the LRFD, he Ultimate limit state, the Fatigue limit state, the Accidental limit state and the Serviceability limit state. As has been stated before, this preliminary analysis does not have a complete structure, but a general design for a sea-fastening system will be implemented. Therefore, the Ultimate limit state will be sufficient to satisfy the objective of the analysis. In general, the analysis for ”Ultimate limit state” consists of calculating the effect of the design load (Sd) and comparing it with that of the resistance (Rd) to obtain results. For this, Sd, which is the most unfavorable effect derived from the design loads that, is obtained through the use of equations directly, usually used for isolated details or it will be obtained by means of software such as the DNV software. The resistance is obtained by experimenting with the materials to determine their true normal resistance factor, which is usually around the design values. And depending on the material it is multiplied by a resistance factor ϕ. Finally being as:

$$Sd < Rd \tag{2.30}$$

Where; Sd = Stress obtained from the software; and, Rd = ϕRk.
Being Rk, a characteristic resistance for a certain condition, that in the case of steel and in the absence of experimental evidence, is taken as 355 MPa, since ϕ is the resistance factor depending on the material defined as:

$$\phi = 1/\gamma_M \tag{2.31}$$

Where γ_M is the factor of the material, in this case steel, which is determined from the following expression [4]:

$$\gamma_M = 1.15 \tag{2.32}$$

Therefore, ec.(2.31) is;

$$\phi = 1/\gamma_M = 0.87 \tag{2.33}$$

And therefore:

$$Rd = \phi Rk = 308.7MPa \tag{2.34}$$

Therefore, the obtained Von-Mises stress by the software should not exceed 308.7 MPa.

Chapter 3

Pre-Procedure, Introduction of the concept and improved design

3.1 Scope

The following sections describe all the steps and procedure followed to perform the dynamic analysis of the catamaran type vessel, wind turbines carrier. For which, three general stages were required: pre-processing, processing and post-processing.

In the first stage, the wind turbines information as dimensions, mass, center of gravity of its parts and position on the vessel were defined. A transportation route was selected to provide realistic data for analysis, which starts on the west coast of Norway and goes to Scotland; and, initial parameters where selected, just as densities, gravity, frequencies, and directions, among others for Hydro-D.

The heeling moment for the wind was calculated for wind speed of 10, 15, 28, 36 and 52 meters per second.

General particulars of the vessel were defined, and from there a series of iterations where performed in accordance with some ”box shaped vessels” and different shapes for the vessel itself analysis. Surface smoothing and preliminary stability analysis where performed to achieve the final shape of the vessel in which the dynamic analysis was applied, as well to ensure that the vessel will support the wind heeling moments and comply with stability criteria.

Which generated a series of numerical models, carried out in Genie de SESAM, with different types of mesh for the panel and structural models of the catamaran vessel. With which it was sought to improve the results of the vessel, and perform the quality check as indicated by DNVGL.

In the process stage, with STABILITY, WADAM and WAMIT, through Hydro-D, the hydrostatic and hydrodynamic analysis was carried out, where:
The GZ curves were obtained, as well as the righting moments of the ship and the comparison with the fulfillment of the stability criteria.

The values of the response amplitude operators, RAO, which are also known as transfer functions or variable response were calculated for the different headings. Conformed by real part, imaginary part, phase angle, and magnitude. Also, the coefficients of added mass and damping were obtained.

In the post-processing stage, the MATLAB tool was used to generate a code in which the wave spectrum and transfer functions are combined to obtain displacements, speeds, and accelerations in specific points of interest of the vessel, such as the bow, the base of the wind turbines and the center of gravity of the nassel and top of the blades of the wind turbine furthest from the center of gravity.

This information was used to generate a general, preliminary sea-fastening design that could support the accelerations to which the WTs are located.

The information of the above processes is indicated in more depth below.

3.1.1 Wind Turbine Description

The wind turbine model selected for the transportation analysis is based on a simplification of the virtual DTU 10-MW reference wind turbine, designed as part of the Light Rotor project which is a collaboration between the Wind Energy Department at the Technical University of Denmark and Vestas.

Which is a horizontal type wind turbine, with the characteristics of the following table. [1]

Table 3.1: Parameters of the DTU 10-MW WT

Parameter	DTU 10MW RWT
Wind Regime	IEC Class 1A
Rotor Orientation	Clockwise rotation - Up wind
Control	Variable Speed, Collective Pitch
Cut in wind speed	4 m/s
Cut out wind speed	25 m/s
Rated wind speed	11.4 m/s
Rated power	10 MW
Number of blades	3
Rotor Diameter	178.3 m
Hub Diameter	5.6 m
Hub Height	119.0 m
Overall Height	208 m
Drivetrain	Medium Speed, MultipleStage Gearbox
Minimum Rotor Speed	6.0 rpm
Maximum Rotor Speed	9.6 rpm
Maximum Generator Speed	480.0 rpm
rpm Gearbox Ratio	50
Maximum Tip Speed	90.0 m/s
Hub Overhang	7.1 m
Shaft Tilt Angle	5.0 deg.
Rotor Precone Angle	-2.5 deg.
Blade Prebend	3.332 m

This model was selected because it represents one of the largest wind turbines that are currently being studied by the industry and those that currently exist.

With the information obtained from the report and attached documents from the HOWC2 [1] page as a base, the general dimensions, mass and center of gravity were specified to be used in the generation of the numerical model. Some of the characteristics were modified such as the case of the nacelle, which is rectangular, so it has a higher drag coefficient.

Table 3.2: General mass and COG for the 10 MW wind turbine with origin in tower base

	Mass (Ton)	x (m)	y (m)	z (m)
Blade_1	41.72	5.80	0.00	148.00
Blade_2	41.72	10.90	-25.00	104.50
Blade_3	41.72	10.90	25.00	104.50
Hub	105.52	7.10	0.00	119.00
Nacelle	446.04	-2.70	0.00	118.00
Tower	628.44	0.00	0.00	47.62
Overall	**1305.15**	**0.53**	**0.00**	**84.29**

The mass of each element, as well as its center of gravity, were clearly specified in relation to a coordinate axis which originates from the center of the base of the wind turbine tower, thus getting the center of gravity of each element described in the report could be taken to the same axis of coordinates.

The projected area of each element, as well as the center of these areas, was generated in AutoCAD, to later calculate the heeling moment for wind. The above information can be found in the annexes section.

3.1.2 Route

The selected route starts on the west coast of Norway and goes to Scotland as stated above. This was selected in agreement with the supervisors, since is approximate to an actual route in which wind turbines where voyaged.

From this route initial parameters where selected. A depth of 300m was assumed as constant. Length of 934.3 Km. Air kinematic viscosity of 1.42e-5 m2/s, air density of 1.226 Kg/m3, water kinematic viscosity of 1.19e-6 m2/s and water density of 1025 Kg/m3 was used as default parameters.

Figure 3.1: Route

The heading for evaluation where selected from 0 to 330 each 30 degrees. Heeling angles for stability analysis starting at -10 until 80 with an step angle of 1. The heeling moment for the wind was calculated for wind speed of 10, 15, 28, 36 and 52 meters per second. The first is the usual expected, the second corresponds to the limit of operation, the third related to the 504 Pa of the intact stability code, and the last two are for DNVGL N-001.11 extreme conditions in which the vessel should never be loaded with wind turbines on board or navigate.

If needed, the expected velocity for the vessel is between 2 and 5 knots with a max of 9 knots without the WT, based on the speed of other wind carriers [24] and the towage of spar WT, even when by agreement with supervisors zero speed can be assumed since it will be low speed transportation.

Scatter diagram of the waves

Data obtained for the specific zones that the route cover. Where significant waves from 0.5 meters to 12.5 meters and up-crossing period Tz from 2 until 12 are presented with its respective probability occurrence value. This data is shown in the figure 3.2 and the plot of it in figure 3.3 to show how concentrated are the probabilities around the Tz 5 and Hs 0.5. This is expected since, small waves are present all the time at sea, meanwhile waves with higher Hs are not as frequent.

		Tz [s]										
		2	3	4	5	6	7	8	9	10	11	12
Hs [m]	0.5	6.678E-05	0.0136593	0.06217	0.0658392	0.0337504	0.0100298	0.001989	0.000301	3.864E-05	0	0
	1	0	0.0021456	0.0241048	0.0482826	0.0429162	0.0215053	0.0068712	0.0015865	0.0002943	4.754E-05	3.95E-06
	1.5	0	0.0005268	0.0111183	0.0344314	0.0431778	0.0298186	0.012846	0.0038871	0.0009173	0.0001832	3.299E-05
	2	0	0.0001393	0.0048969	0.021642	0.0355818	0.031307	0.0168715	0.0062541	0.0017696	0.0004153	8.615E-05
	2.5	0	3.855E-05	0.0021071	0.0126804	0.02626	0.0281997	0.0182269	0.0079648	0.0026114	0.0006988	0.0001628
	3	0	0.000011	0.0008929	0.0070927	0.0180359	0.0230078	0.0173607	0.0087222	0.0032405	0.0009693	0.0002493
	3.5	0	0	0.0003738	0.003834	0.0117615	0.0174948	0.0151232	0.0085834	0.0035566	0.0011727	0.0003289
	4	0	0	0.0001531	0.0020173	0.0073688	0.0126084	0.012314	0.0077928	0.0035589	0.00128	0.000388
	4.5	0	0	6.283E-05	0.0010377	0.004469	0.008706	0.0095045	0.0066389	0.0033112	0.0012884	0.000419
	5	0	0	2.553E-05	0.0005234	0.0026371	0.0058022	0.0070212	0.0053697	0.0029034	0.0012143	0.0004213
	5.5	0	0	1.027E-05	0.0002594	0.0015196	0.0037519	0.0049985	0.0041581	0.0024228	0.0010834	0.000399
	6	0	0	0	0.0001265	0.0008574	0.0023633	0.003447	0.0031022	0.0019381	0.0009224	0.0003593
	6.5	0	0	0	6.081E-05	0.0004746	0.0014543	0.0023117	0.0022406	0.0014947	0.0007544	0.0003098
	7	0	0	0	2.694E-05	0.0002582	0.0008764	0.0015125	0.0015727	0.0011163	0.0005956	0.0002571
	7.5	0	0	0	1.262E-05	0.0001382	0.0005182	0.0009678	0.0010763	0.0008104	0.0004558	0.0002063
	8	0	0	0	0	7.286E-05	0.0003011	0.000607	0.0007199	0.0005736	0.0003393	0.0001607
	8.5	0	0	0	0	3.787E-05	0.0001721	0.0003738	0.0004717	0.0003968	0.0002464	0.000122
	9	0	0	0	0	1.621E-05	9.693E-05	0.0002263	0.0003034	0.0002689	0.000175	9.036E-05
	9.5	0	0	0	0	8.27E-06	5.381E-05	0.0001349	0.0001918	0.0001789	0.0001218	6.554E-05
	10	0	0	0	0	0	2.948E-05	7.927E-05	0.0001194	0.0001171	0.0000833	4.665E-05
	10.5	0	0	0	0	0	1.594E-05	4.596E-05	7.325E-05	7.541E-05	5.604E-05	3.263E-05
	11	0	0	0	0	0	6.51E-06	2.631E-05	4.436E-05	4.792E-05	3.716E-05	2.248E-05
	11.5	0	0	0	0	0	0	1.489E-05	2.654E-05	3.006E-05	2.431E-05	1.528E-05
	12	0	0	0	0	0	0	0	0.0000157	1.864E-05	1.572E-05	6.81E-06
	12.5	0	0	0	0	0	0	0	0	6.48E-06	7.85E-06	6.87E-06

Figure 3.2: Scatter diagram datta

Wave Spectrum

For the further analyses the wave spectrum was obtained for the same Hs and the Tz that are present in the scatter diagram. Aditional to this the wave angular frequency ω was defined to ensure sufficient number of magnitudes for the spectra. In the previous chapter the equations used to get the values for the Pierson-Moskowitz Spectrum S(ω) are presented. Also is interesting to notice that the higher the Tz period is and the higest Hs it has, the narrow the spectrum gets.

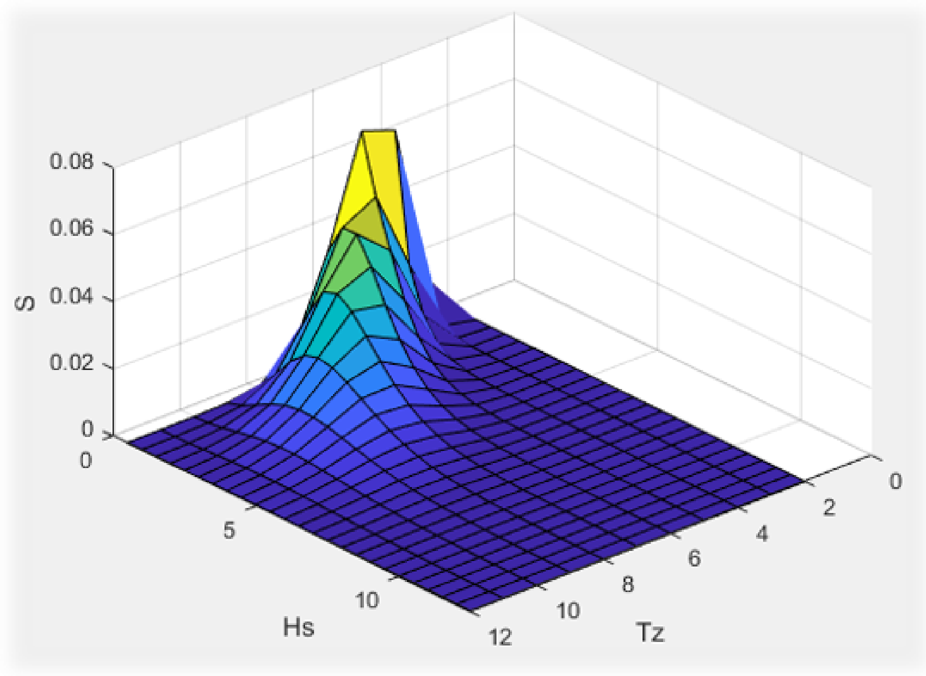


Figure 3.3: Scatter diagram

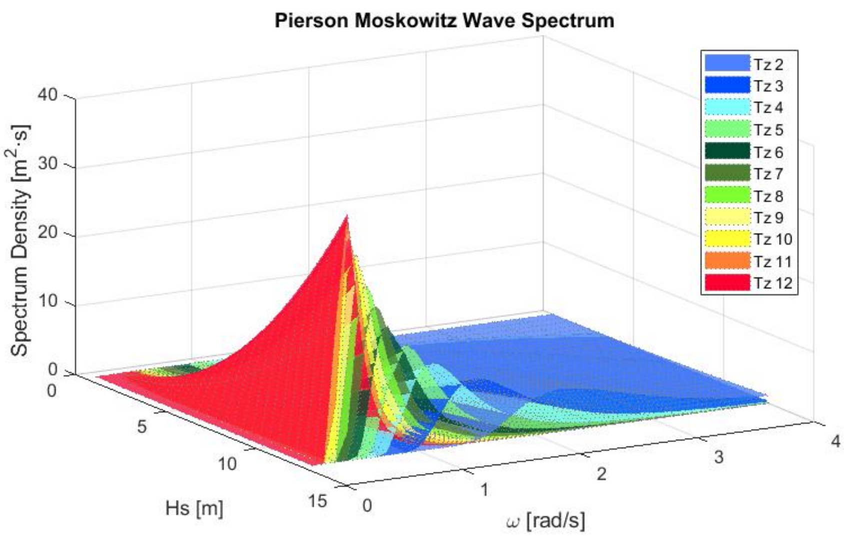


Figure 3.4: Pierson-Moskowitz Spectrum, for wave frequencies of 0.2:4, Hs of 0.5:0.5:12.5 and Tz 2:12.

3.1.3 Catamaran WT Installation Vessel Description

The vessel forms were selected after the modification of an initial model provided by the supervisor to which modifications were applied based on a stability analysis performed on different ship models.

Some of this models where rectangular parallelepiped and with a length of 130 m corresponding to the length of the water line of the initial container. With different beams, heights, draughts, centers of gravity, distance between amas and midsection shape. The description of these models, as well as the GZ curves of them, can be found in the annexes section. The other models where some trials of proposals for the shape of the vessel.

For the case of the mass of the vessel, first the displacement of it to the waterline corresponding to 8 meters from the baseline was calculated and the weight corresponding to four wind turbines installed on deck was subtracted.

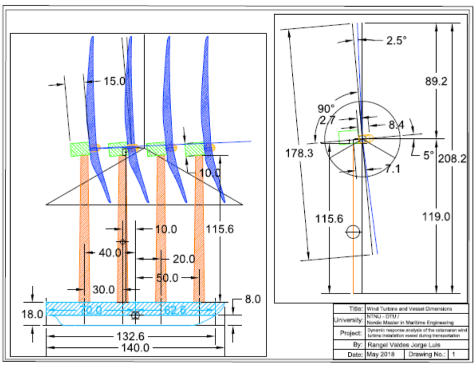


Figure 3.5: Vessel plan and WT location

These were located with the center of the base of the tower, which corresponds to the axis of coordinates of the wind turbines, 30 meters from each other, placing the second WT (from stern to bow) at 10 meters astern of the middle section. With this information, it was possible to calculate the total weight of the ship alone (without wind turbines) and the longitudinal center of gravity. The transverse center of gravity was located on the center line. For the rest of the document the wind turbine located FW on the vessel will be referred as WT1 and continue to the one located Aft which will be named WT4. Plans of the vessel and the location of the wind turbines where done to ensure the location of the center of gravity of each element, projected areas for wind moments. They can be found in the Annexes.

For the vertical center of gravity first was assumed two situations, one with the center of gravity of the vessel on deck, which correspond to the worst case scenario for the ship from the stability perspective but the best scenario for the motion analysis; and a second scenario where the KG was located two meters above the KB, which correspond a good scenario from stability perspective but a bad one for the motions analysis. With this the final result of the catamaran vertical center of gravity will be somewhere in between when the structural design and specific subdivision of the vessel came into account, giving flexibility and conservative approach for the analysis.

Having the total weight and the two scenarios of the center of gravity of the vessel, plus the weight and center of gravity of the wind turbines then the overall center of gravity and mass, for two loading conditions can be specified.

The catamaran wind turbine installation vessel has the following particulars:

Table 3.3: Vessel Particulars

Type	Catamaran
Amas	Symmetric
Length over all [m]	140
Aft Perpendicular [m]	70
Forward Perpendicular [m]	62.6
Waterline Length [m]	132.6
Beam overall [m]	60
Cross section Height [m]	5
Buoyancy volume [m^3]	16843.2
Buoyancy mass [Ton]	17264.3
Center of buoyancy X [m]	-2.81359
Center of buoyancy Y [m]	0
Center of buoyancy Z [m]	4.28014
Center of flotation X [m]	-2.82532
Center of flotation Y [m]	0
Center of flotation Z [m]	8
Waterline area [m^2]	2497.05
Trim moment [N*m]	34699300000
Panel model block coefficient	0.260602
Projected XZ area above waterline [m^2]	7505.46
Center proj. XZ area above X [m]	6.55846
Center proj. XZ area above Z [m]	84.2398
Projected XZ area below waterline [m^2]	929.087
Center proj. XZ area below X [m]	-2.50901
Center proj. XZ area below Z [m]	-3.86254
Metacentric Height GM [m]	54.6881
Buoyancy mass [Ton]	17264.3
Center of vessel mass X [m]	-6.43
Center of vessel mass Y [m]	0
Center of vessel mass Z [m]	18 and 6

3.1.4 Preliminary results in order to improve the vessel design

For ensuring to fulfill the stability criteria, an improvement of the hull was made, at the same time that the smooth between points was considered, if the hull has lot of deformations, leads to a bad mesh quality, where may cause that the values for certain frequencies become inaccurate.

3.1.5 Smoothing of the values from the offset Table

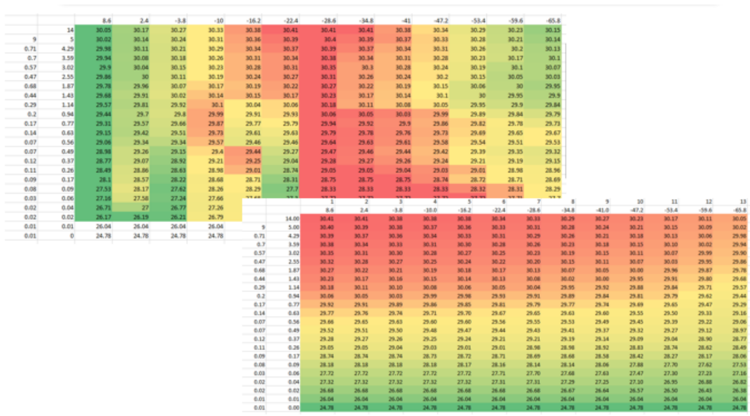


Figure 3.6: Vessel Aft Offset table, before and after smoothing.

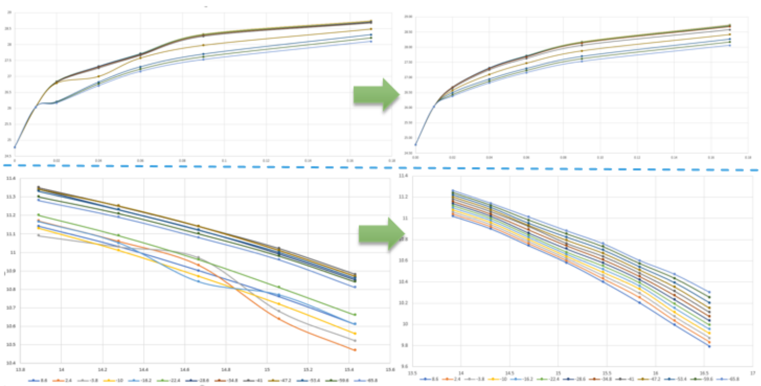


Figure 3.7: Water lines before and after smoothing

The difference between the waterlines are shown, where it can be easily noticed that the smooth is not enough. Since it is a FEM model, all the guide geometry will make an influence in the final mesh for the analysis.

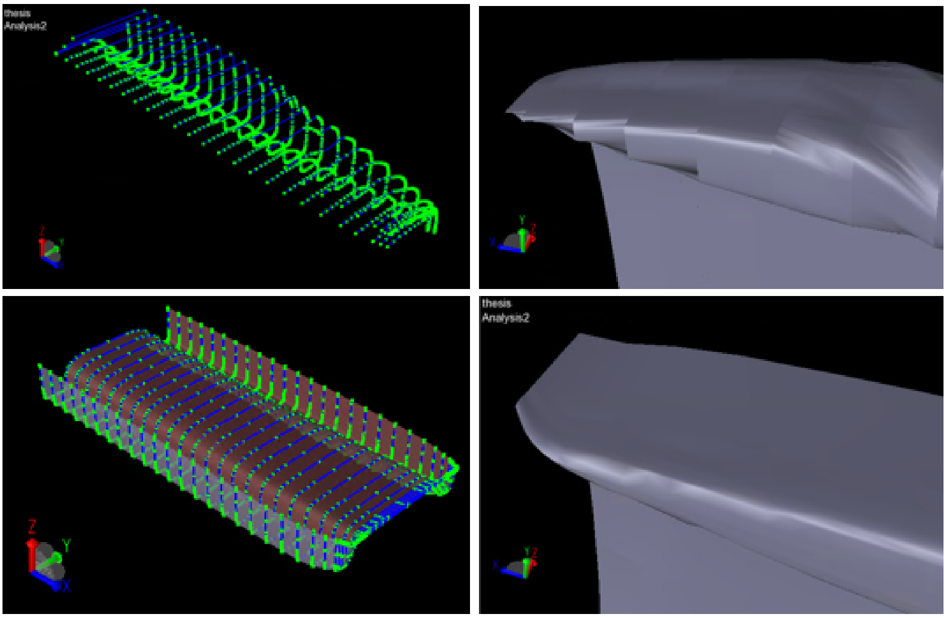


Figure 3.8: Numerical model plates with and without smoothing. (also some extra modification was performed at the bow at this stage)

An exceed of guide point also tends to concentrate to much the calculations in specific areas pushing the elements to be smaller and to be considered with bad shape.

3.1.6 ”Box shaped vessels” analyses

Distance between Amas_Depth_VCG_WL — Base= 20 15 15 5

Per ama			Amas Separation	Depth differences	VCG Differences	Underwater Diff.	FB	Load. Conditions	Hydro M	Disp. Kg
				0 11 15 5				00_11_15_05	1	13325000
Per ama					0 15 5 5			00_15_05_05	2	13325000
	(m)	Mono	0 15 15 5	0 15 15 5	0 15 15 5	0 15 15 5	10	00_15_15_05		13325000
L	130				0 15 20 5			00_15_20_05		13325000
B	10			0 21 15 5				00_21_15_05	3	13325000
WP_area	1300					0 21 15 11	10	00_21_15_11*		29315000
Ix'	10833.33	Multi	10 15 15 5					10_15_15_05	4	13325000
Iy'	1830833			20 11 15 5				20_11_15_05	5	13325000
					20 15 5 5			20_15_05_05	6	13325000
CrossSecc.			20 15 15 5	20 15 15 5	20 15 15 5	20 15 15 5	10	20_15_15_05		13325000
D	5				20 15 20 5			20_15_20_05		13325000
Iz´ Cross S	915416.7				20 15 50 5			20_15_50_05		13325000
				20 21 15 5				20_21_15_05	7	13325000
						20 21 15 11	10	20_21_15_11*		29315000
			30 15 15 5					30_15_15_05	8	13325000

EXTRA (All based in 20_15_15_5)		Load. Conditions	Hydro M	Disp. Kg
	Full beam of 40	Barge	9	26650000
		Piramid	10	3331250
	WP_area vs Disp	triangular_1	11	3331250
	WP_area vs Disp	triangular_2	12	29315000
	WP_area vs Disp	triangular_3	13	4996875
		triangular_inv	14	3331250
		CrossS_Long	15	13325000
		CrossS_Short	16	13325000

Load. Conditions	
LC_5	5
LC_11	11

Figure 3.9: Different Box Shaped Vessels that where analyzed.

The vessel is intend to fulfill the correspondent criteria, therefore in DNVGL-N001, section 11 that take consideration for sea voyage operations, indicate that the vessel should comply with the stability criteria and the survival wind heeling moment by an additional 40 percent. So, an improvement of the hull was performed. For this, and to extend the knowledge of catamaran vessels against monohull, and also with different parameters involved such as the draft, the shape of GZ, reaction to different position of the center of gravity among others; a simple stability analysis where performed to vessels that are composed by rectangular shapes with length of 130m and cross section of 5m high as constants. In the figure 3.9 the different considerations are described.

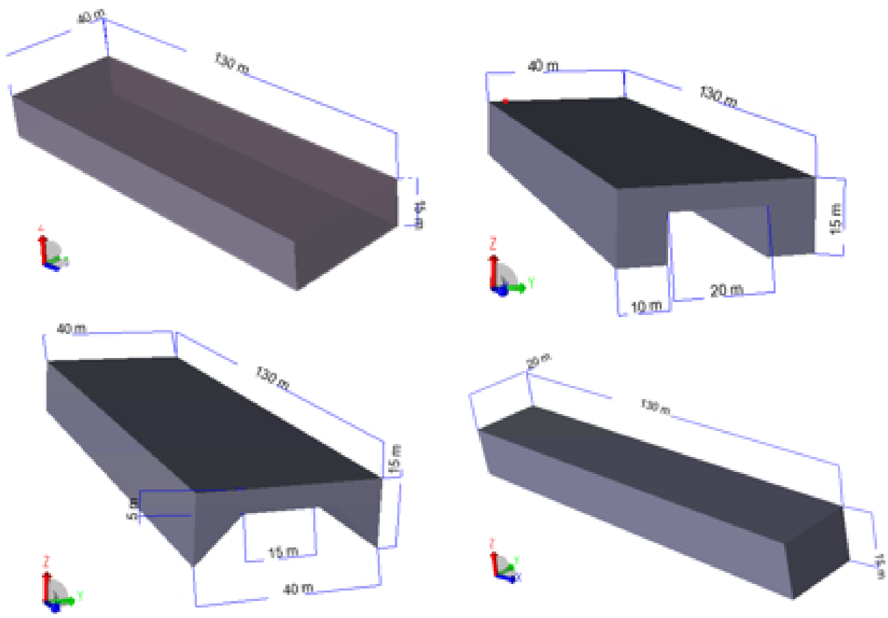


Figure 3.10: Some of the Box Shaped Vessels of the analyses.

The GZ curves for the particular case of the barge against the catamaran and a catamaran with triangular amas is presented. The GM is influenced by the second moment of the area of the waterplane over the volume displaced, then the configuration of the triangular shape, that have almost same waterplane area as the rectangular catamaran but less displacement presents bigger GZ than the other ships. The particular case of the monohull with the same displacement of the rectangular catamaran could not stand the relatively small high CG of 15m. It is said relatively small since the original vessel should stand a CGz of around 30m. A important difference with mono-hulls is that the GZ curve star to decrease in the moment that the deck reach the waterline, meanwhile for catamaran vessels, the curve decrease immediately when one of the amas goes out of the water, since there is a loss in the second moment of the area, and therefore the heel angle for the max GZ will not be as long as for monohull. Also is interesting to notice that, for the plot of the moments for the same vessels, the triangular catamaran with lower displacement does not show as big moments as the other two; also, the catamaran and the barge even with different displacement, have similar moments in general, but the area under the curve for the rectangular shape is the best option.

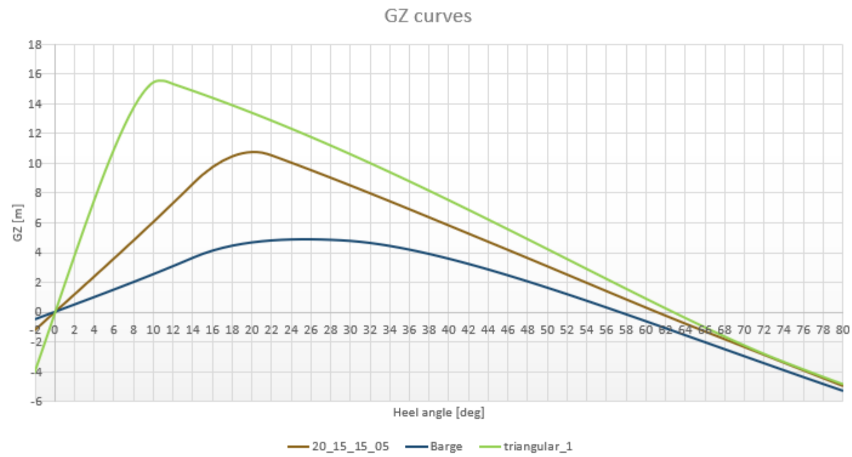


Figure 3.11: GZ curves for three of the box shaped vessels

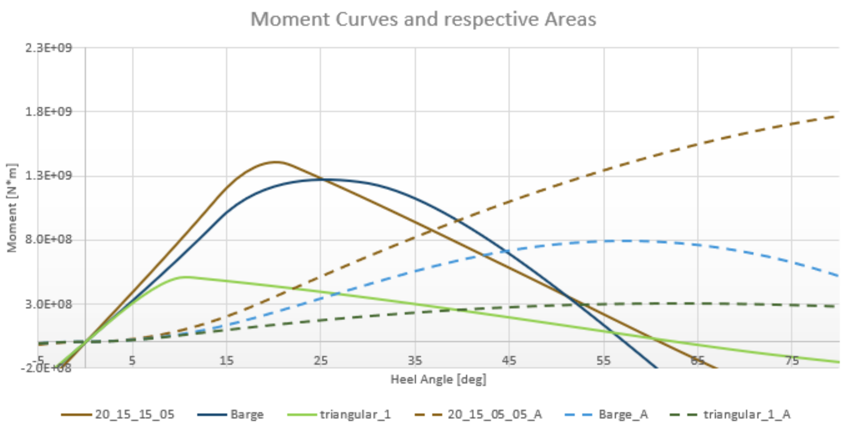
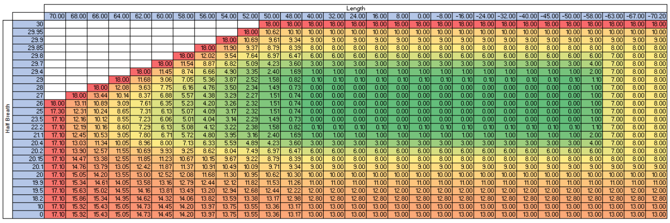


Figure 3.12: Moments and moment area curves for three of the box shaped vessels

Similar assumptions where made for the other comparisons, and the GZ curves and Moment curves can be found in the Annexes.

3.1.7 Final Offset Table

After performing the past analysis and study on catamarans and mono-hulls, smoothing the surface and distribute evenly the guiding points, the final Offset Table is presented. Some of the main difference is that it has amas a bit more narrow than the original but the general section of the amas are quite straight, which can be beneficial for the construction procedure, which try to simplify the steel management procedures, since a catamaran vessel already have lot of complexity in the structure as stated above. Also the bow is more wide, since the speed of the vessel is not a priority, and in that way the space for the propulsion system, which provably will be azimuth system, was created. There is not an application of free-board, since the height of it need a specific calculation t fulfill the code of Load Lines. The free-board will help to increase the range of stability, but not help as much as helps in the case of mono-hulls since the lost of waterplane is the important factor as stated above. A plot with a proper size of the offset table can be found in the annexes.



Half Breath \ Length	70.00	68.00	66.00	64.00	62.00	60.00	58.00	56.00	54.00	52.00	50.00	48.00
30											18.00	18.00
29.95										18.00	10.62	10.10
29.9									18.00	10.69	9.61	9.34
29.85								18.00	11.90	9.37	8.79	8.39
29.8							18.00	12.02	9.54	7.64	6.97	6.47
29.7						18.00	11.54	8.87	6.82	5.09	4.23	3.60
29.4					18.00	11.45	8.74	6.66	4.90	3.35	2.40	1.69
29				18.00	11.68	9.06	7.05	5.36	3.87	2.52	1.58	0.82
28			18.00	12.08	9.63	7.75	6.16	4.76	3.50	2.34	1.49	0.73
27		18.00	13.44	10.14	8.37	6.88	5.57	4.38	3.29	2.27	1.51	0.74
26	18.00	13.11	10.89	9.09	7.61	6.35	5.23	4.20	3.26	2.32	1.51	0.74
25	17.30	12.31	10.24	8.65	7.31	6.13	5.07	4.09	3.17	2.32	1.51	0.74
23.5	17.10	12.16	10.12	8.55	7.23	6.06	5.01	4.04	3.14	2.29	1.49	0.73
22.2	17.10	12.19	10.16	8.60	7.29	6.13	5.08	4.12	3.22	2.38	1.58	0.82
21.1	17.10	12.45	10.53	9.05	7.80	6.71	5.72	4.80	3.95	3.16	2.40	1.69
20.4	17.10	13.03	11.34	10.05	8.96	8.00	7.13	6.33	5.59	4.89	4.23	3.60
20.2	17.10	13.90	12.57	11.55	10.69	9.93	9.25	8.62	8.04	7.49	6.97	6.47
20.15	17.10	14.47	13.38	12.55	11.85	11.23	10.67	10.15	9.67	9.22	8.79	8.39
20.1	17.10	14.76	13.79	13.05	12.42	11.87	11.37	10.91	10.49	10.09	9.71	9.34
20	17.10	15.05	14.20	13.55	13.00	12.52	12.08	11.68	11.30	10.95	10.62	10.30
19.9	17.10	15.34	14.61	14.05	13.58	13.16	12.79	12.44	12.12	11.82	11.53	11.26
19.5	17.10	15.63	15.02	14.55	14.16	13.81	13.49	13.20	12.94	12.68	12.44	12.22
18.2	17.10	15.86	15.34	14.95	14.62	14.32	14.06	13.82	13.59	13.38	13.17	12.98
10	17.10	15.92	15.43	15.05	14.73	14.45	14.20	13.97	13.75	13.55	13.36	13.17
0	17.10	15.92	15.43	15.05	14.73	14.45	14.20	13.97	13.75	13.55	13.36	13.17

Half Breath \ Length	40.00	32.00	24.00	16.00	8.00	0.00	-8.00	-16.00	-24.00	-32.00	-40.00	-45.00	-50.00	-58.00	-63.00	-67.00	-70.20
30	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
29.95	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
29.9	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
29.85	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
29.8	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	7.00	8.00	8.00
29.7	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	7.00	8.00	8.00
29.4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	7.00	8.00	8.00
29	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.10	7.00	8.00	8.00
28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.00	8.00	8.00
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.00	8.00	8.00
26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.00	8.00	8.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.00	8.00	8.00
23.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.00	8.00	8.00
22.2	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.10	7.00	8.00	8.00
21.1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	7.00	8.00	8.00
20.4	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	7.00	8.00	8.00
20.2	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	7.00	8.00	8.00
20.15	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
20.1	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
20	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
19.9	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00
19.5	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
18.2	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80	12.80
10	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00
0	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00

Figure 3.13: Final Vessel Offset table.

3.1.8 Numerical Models

As stated before, different mesh was selected to perform a quality check of 6 different size of mesh.

Mesh Quality Check of Numerical Models

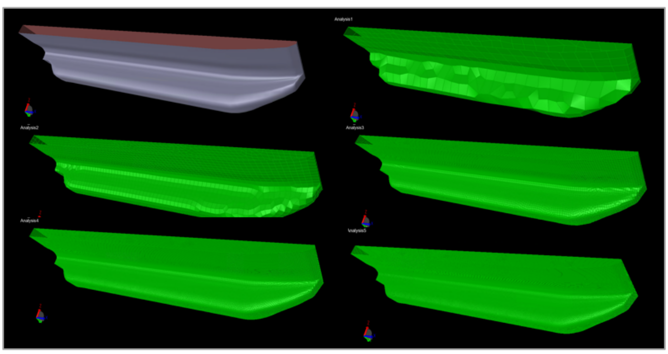


Figure 3.14: Different mesh analyzed to perform the quality check

As it can be see the different mesh produces that the shape of the vessel will be different for the very coarse mesh where even the displacement of the vessel is different of the rest of the models. Also it can be noticed the time spent for the different meshing, the ones for the low CG was performed without an offset point on the sea surface, therefore a big difference in time can be reached. For comply the criteria of the minimum 4 panels per wavelength the medium size mesh will be sufficient to perform the analysis at this design stage. Also a combination of different mesh was applied to a model in which was not really of time benefit. The very Fine mesh presents problems to generate the mesh with considerable enough amount of time.

	Model Id.	Center of Gravity	Mesh	Max Panel size Underwater [m]	No. of Elements [#]	Min Wave Length [m]	Panels per wave length* [-]	CAT. ZCG [m]	ZCG [m]	Cpu mesh time [s]	Displacement [ton]	CPU Stab [s]	CPU RAO time [s]
Panel Model	1	Hcg	Very Coarse	5	510	4.13	0.8	18.00	45.90	8	15598.95	1	123
		Lcg						10.00	37.92			1	43
	2	Hcg	Coarse	2	3140	4.13	2.1	18.00	43.49	52	17072.43	6	192
		Lcg						10.00	35.16			6	57
	3	Hcg	Medium	0.78	20152	4.13	5.3	18.00	43.21	293	17264.29	35	1206
		Lcg						10.00	34.84			32	565
	4	Hcg	Fine	0.52	44816	4.13	8.0	18.00	43.18	723	17285.18	73	3747
		Lcg						10.00	34.80			68	2676
	5	Hcg	Very Fine	0.42	69361	4.13	9.9	18.00	43.17	1462	17291.52	NA	NA
		Lcg						10.00	34.79			NA	NA
	6	Hcg	Combination	0.78	12658	4.13	5.3	18.00	43.21	340	17264.88	19	1208
		Lcg						10.00	34.84			21	593
Structural Model	S		Medium Comb.	0.78	32264		8			550			

*DNVGL-RP= Minimum 8 panels un a wave length

Figure 3.15: Comparison between different meshing.

Frequency Range Selection

An important criteria that is coupled to the mesh size and the wavelength is the angular frequency, wich has been analyzed to obtain sufficient point for a fair range or ang. frequencies.

	start	end or converge	unit	ref
important wave length	264	16.5	lambda	
	0.48	1.93	w	
Wave spectrum	0.2	8	w	matlab
Vessel Responses Expected	18	4	s	dync
	0.314	1.57	w	
Rules	16.6	2.55	s	DNVGL N-001
	0.38	2.46	w	
Analisis	0.4	2	w	

Figure 3.16: Criteria for initial selection of wave frequency

Chapter 4

Procedure for Transportation Analyses; including both hydro-static and hydrodynamics of the catamaran vessel

4.1 Scope

The next sections include the steps performed to cover the objective of the thesis report. Since there are different wave periods, and headings, not all the plots are shown, just a couple of each one that is needed to proceed with the next step. At the end the analysis was carried for all the values and the final values of MPM for displacement, velocities and accelerations in the different points of interest where obtained.

4.2 Intact stability analysis

The criteria for the intact stability of catamaran bigger than 100m, and low speed are not exitent. Therefore, a combination of the different criteria was coupled to the Offshore supply vessel, that can be considered the most complete criteria for the vessel, as stated above.

In the figure 4.1, the offshore supply vessel, the intact general, and pontoons criteria where merged. HydroD was selected to perform the stability analysis, for long heeling angles

Offshore supply vessels With Max. GZ under 30° (Offshore)	Stability criteria			Code IS part A, 2.2.1	Code IS part B, 2.4.5.2.1	Code IS part A, 2.2.1	Code IS part B, 2.4.5.2.2	Code IS part B, 2.4.5.2.3	Code IS part B, 2.4.5.2.4	Code IS, part B, 2.2.4.3	Code IS part B, 2.4.5.2.5	Code IS part A, 2.3.1.4	
				Area under GZ from 0° to 30°	GZ-Area until max angle, if this is between 15 and 30°	Area under GZ from 0° to 40°	30-40 or 30-Φ	Righting Arm GZ 30	Max Righting Arm Angle	The minimum range of stability: (by interpolation)	Metacentric Hight GM	The area **B** should be equal or bigger than area **A**	Angle of vanishing stability
Condition	Draft (m)	V Desp. (m³)	CGz (m)*	>0.055 m-rad 3.151 m-grad	0.055+0.001(30°-ΦMax) m-rad	>0.09 m-rad 5.157 m-grad	>0.03 m-rad 1.719 m-grad	>0.2 m	>15°	20° if L ≤100m 15° if L ≥150m	>0.15 m	**B>A**	-

(blue)	General IS criteria
(yellow)	Offshore suply Vessels
(pink)	Pontoons

*Values from baseline

Figure 4.1: GZ Curves of the vessel.

ranging from -10 to 80 in steps of 1 degree. The values where obtained and are presented in the results chapter.

4.2.1 Wind Heeling Force and Moment

As it can be seen in figure 3.5, the projected area of the different sections of the loaded catamaran vessel were obtained. Then, the force from the wind, in relationship to its speed can be obtained with the method described in the rules [5] section 11. An example of the values considered are shown in figure 4.2. Where;

Cs = The shape coefficient depending on the shape of the structural member exposed to the wind (Table 1 [7])
Ch = The height coefficient depending on h
h = Theheight above sea level of the structural member exposed to wind (see Table 2 [7])
P=1.222 =The air mass density [kg/m3]
V=36 =The wind velocity [m/s], see note 2.1.2[7]
A = The projected exposed surfaces area in either the upright or the heeled condition [m^2]

Air Density=	V=
1.226	28

	Cs	h	Ch	Area	Force	F* 4WT	
Vessel	1.00	5.04	1.00	1373.02	659862.43	659862.43	
Tower	0.50	62.40	1.37	797.00	262376.80	1049507.20	
Nacelle	1.00	128.85	1.56	150.00	112458.53	449834.11	
Up.Blade	1.30	164.80	1.63	403.00	410404.90	1641619.61	
Dw.Blade	1.30	113.00	1.52	176.00	167138.36	668553.45	
Hub	0.50	129.80	1.56	42.45	15912.88	63651.53	
Total		87.37		7646.82		4533028	N
Underwater area arm		3.13					
	Total Arm	90.5	m				

Pressure	592.7991411	Pa
Moment	410.2390637	MN*m

Figure 4.2: Obtention of the wind force and moment for the case of wind speed of 28 m/s, upright heel angle and from perpendicular direction to the vessel.

The chart of the complete values obtained for different heel angles, and for different wind speed is shown in figure 4.3. This values where compared to the result of the software, wich varies only for less than 1 percent.

	Moments					Moment Area				
	Wind Speed [m/s]					Wind Speed [m/s]				
	10	15	28	36	52	10	15	28	36	52
0	5.25E+07	1.18E+08	4.11E+08	6.80E+08	1.42E+09	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	5.14E+07	1.16E+08	4.03E+08	6.66E+08	1.39E+09	4.53E+06	1.02E+07	3.55E+07	5.87E+07	1.23E+08
10	5.17E+07	1.16E+08	4.05E+08	6.70E+08	1.40E+09	9.03E+06	2.03E+07	7.07E+07	1.17E+08	2.44E+08
15	5.13E+07	1.15E+08	4.01E+08	6.65E+08	1.39E+09	1.35E+07	3.04E+07	1.06E+08	1.75E+08	3.66E+08
20	5.21E+07	1.17E+08	4.08E+08	6.75E+08	1.41E+09	1.80E+07	4.06E+07	1.41E+08	2.34E+08	4.87E+08
25	4.84E+07	1.08E+08	3.79E+08	6.27E+08	1.31E+09	2.24E+07	5.04E+07	1.75E+08	2.90E+08	6.06E+08
30	4.60E+07	1.03E+08	3.60E+08	5.97E+08	1.25E+09	2.65E+07	5.97E+07	2.08E+08	3.44E+08	7.17E+08
35	4.32E+07	9.72E+07	3.30E+08	5.60E+08	1.17E+09	3.04E+07	6.85E+07	2.30E+08	3.94E+08	8.23E+08
40	4.02E+07	9.05E+07	3.15E+08	5.22E+08	1.09E+09	3.41E+07	7.66E+07	2.67E+08	4.41E+08	9.21E+08
45	3.73E+07	8.38E+07	2.92E+08	4.83E+08	1.01E+09	3.74E+07	8.43E+07	2.90E+08	4.85E+08	1.01E+09
50	3.44E+07	7.73E+07	2.60E+08	4.45E+08	9.29E+08	4.06E+07	9.13E+07	3.10E+08	5.26E+08	1.10E+09
55	3.24E+07	7.28E+07	2.53E+08	4.20E+08	8.75E+08	4.35E+07	9.78E+07	3.40E+08	5.64E+08	1.18E+09
60	2.94E+07	6.62E+07	2.30E+08	3.81E+08	7.95E+08	4.62E+07	1.04E+08	3.60E+08	5.98E+08	1.25E+09
65	2.71E+07	6.10E+07	2.13E+08	3.51E+08	7.33E+08	4.86E+07	1.09E+08	3.81E+08	6.30E+08	1.32E+09
70	2.30E+07	5.17E+07	1.80E+08	2.98E+08	6.21E+08	5.08E+07	1.14E+08	3.98E+08	6.59E+08	1.37E+09
75	1.96E+07	4.40E+07	1.53E+08	2.54E+08	5.29E+08	5.27E+07	1.19E+08	4.13E+08	6.83E+08	1.42E+09
80	1.70E+07	3.82E+07	1.33E+08	2.20E+08	4.59E+08	5.43E+07	1.22E+08	4.26E+08	7.03E+08	1.47E+09

Figure 4.3: Chart with complete moments and areas under the moment curve obtained.

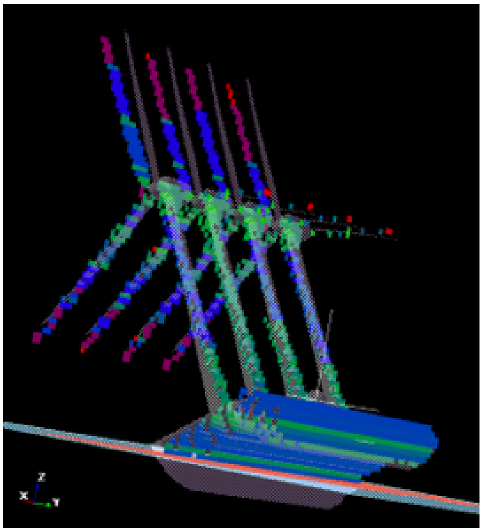


Figure 4.4: Comparison of the wind heeling moment where performed on HydroD

The moment for different wind speed where obtain as the area under the curve, which are the values that the righting arm and moment should pass. In the particular case of the wind speed, since is assumed navigation in good weather, and the 36 m/s is already corresponding to hurricane winds at Beaufort scale, even it was calculated, it is not taken into consideration for the analysis. Then the biggest moment to fulfill will be the 36 m/s moment curve.

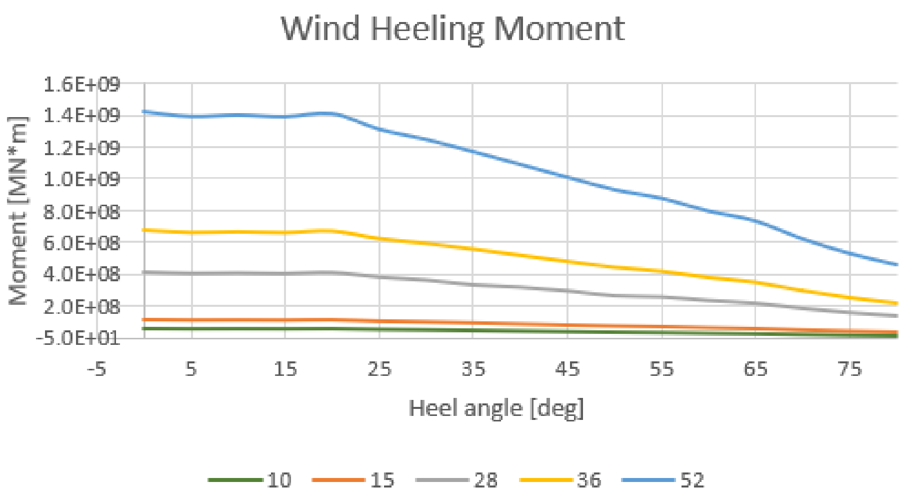


Figure 4.5: Wind moment curves.

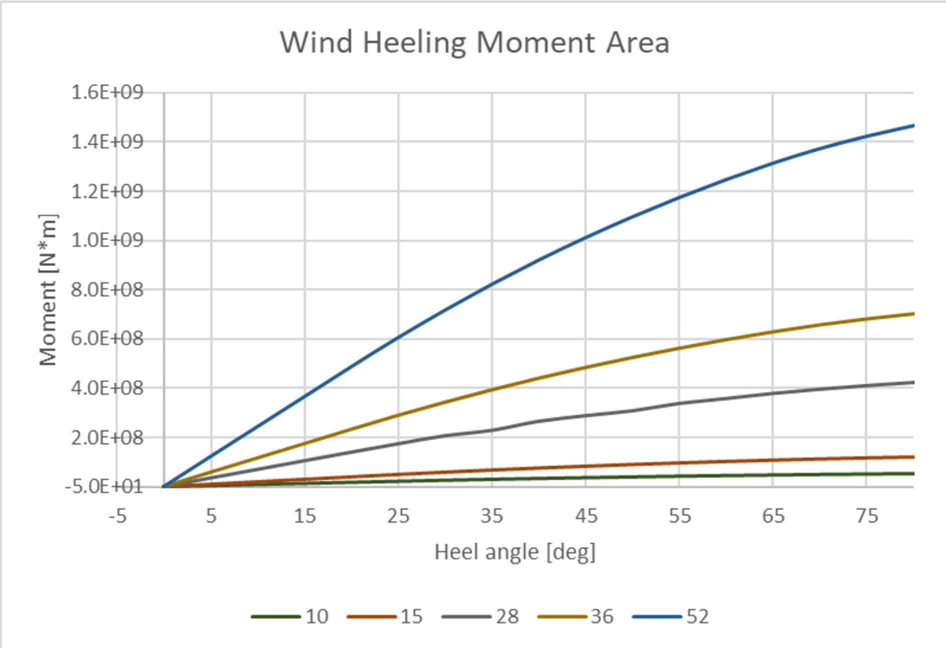


Figure 4.6: Area under wind moment curves.

4.3 Vessel Dynamic Analysis using the frequency-domain approach

4.3.1 RAO's of the vessel

The following section presents the obtained by WADAM and WAMIT, and which values are used to post-process with MATLAB the response, to calculate the most probable maximum of the vessel. The RAOs are presented for the vessel, for all headings but it can be noticed that the symmetric headings present the same results.

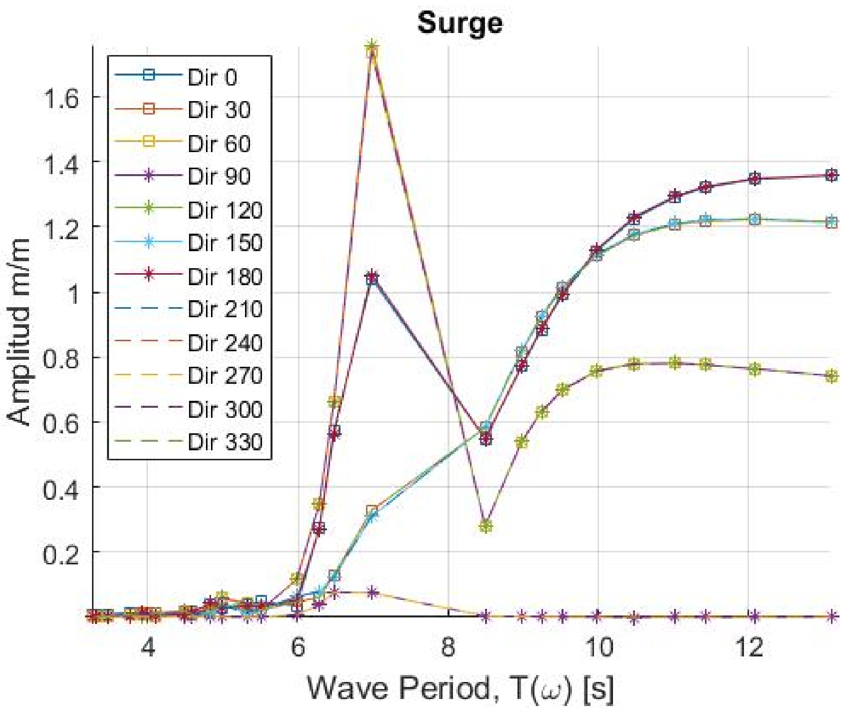


Figure 4.7: RAO for Surge

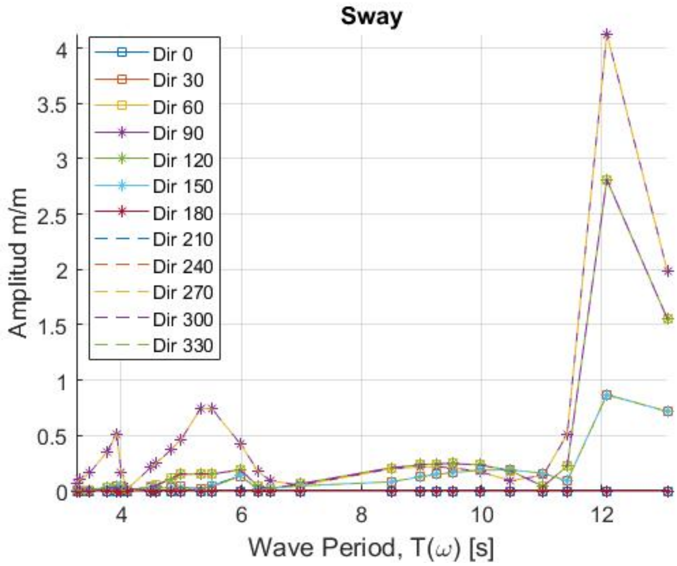


Figure 4.8: RAO for Sway

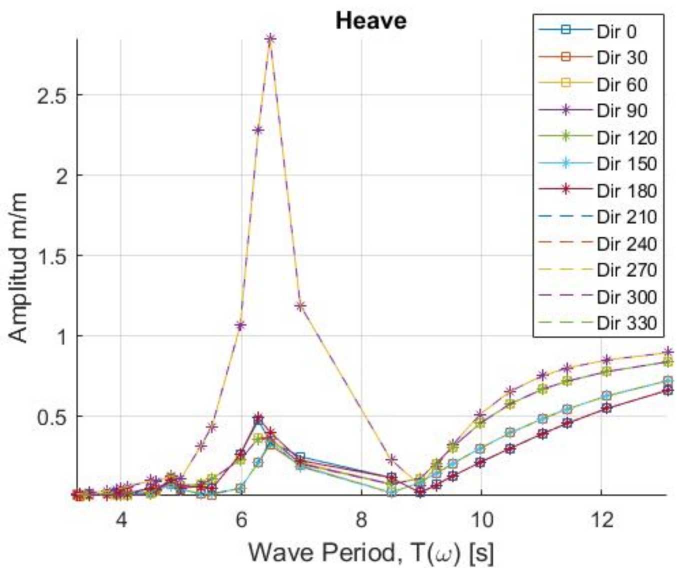


Figure 4.9: Rao for Heave

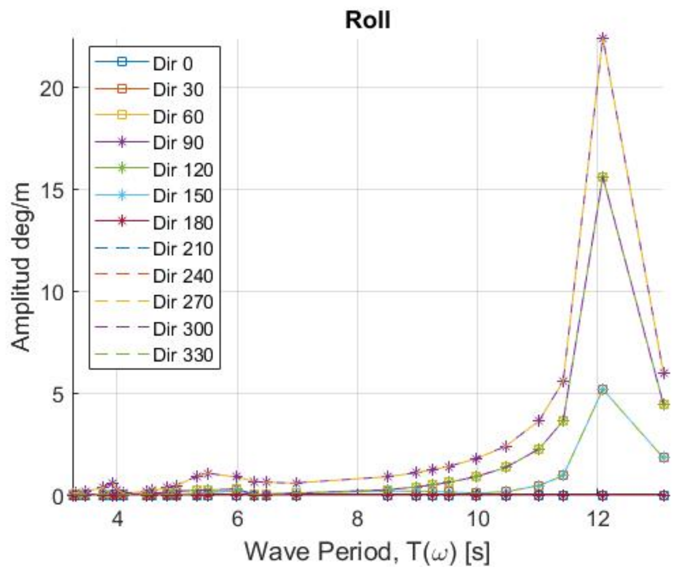


Figure 4.10: Rao for Roll

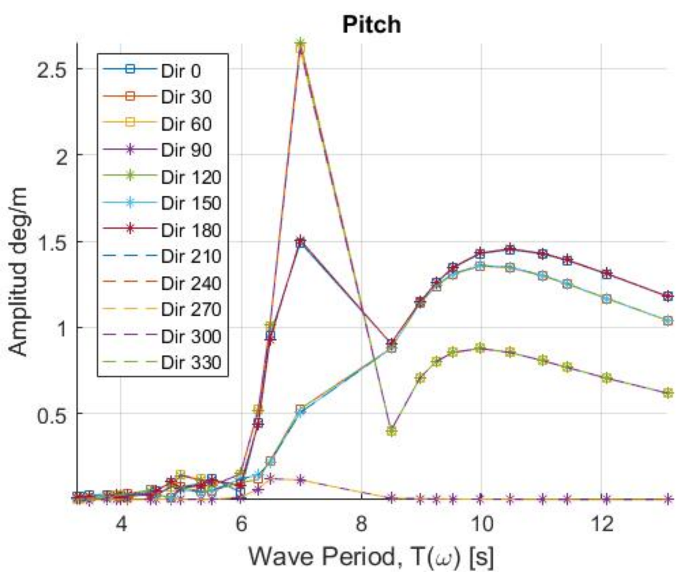


Figure 4.11: RAO for Pitch

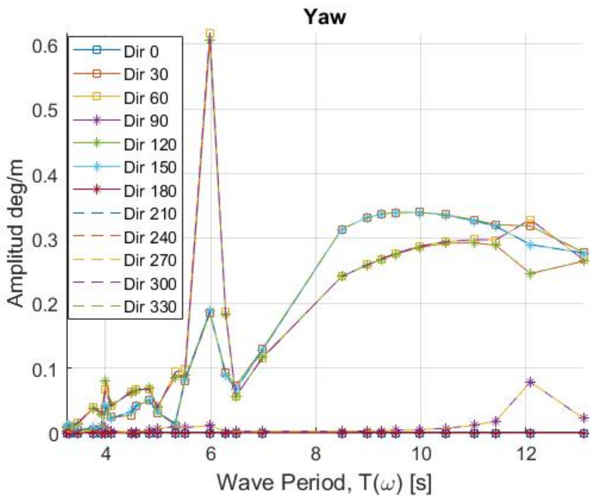


Figure 4.12: RAO for Yaw

4.3.2 Transfer functions for specific point results

The RAO's obtained where coupled as stated in the method section and in this particular case applied for the specific point that represent the base of the WT1 tower [52.81,0,10], this point is referred to the Water plane axis, that is 2.81 meters Aft the mid section and 8m above the base line.

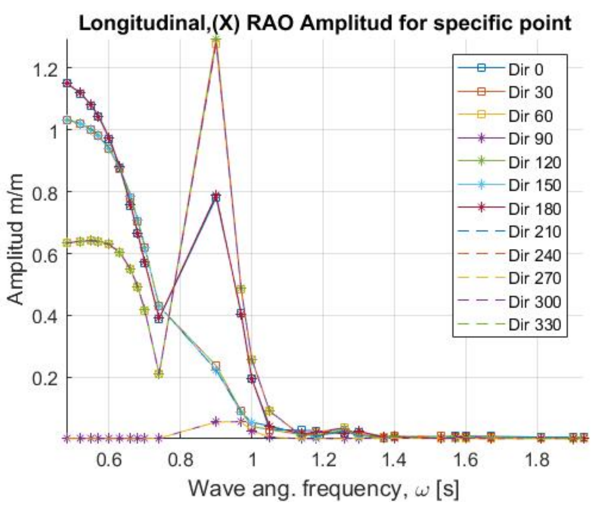


Figure 4.13: RAO for specific point, referred to X axis, for WT1B

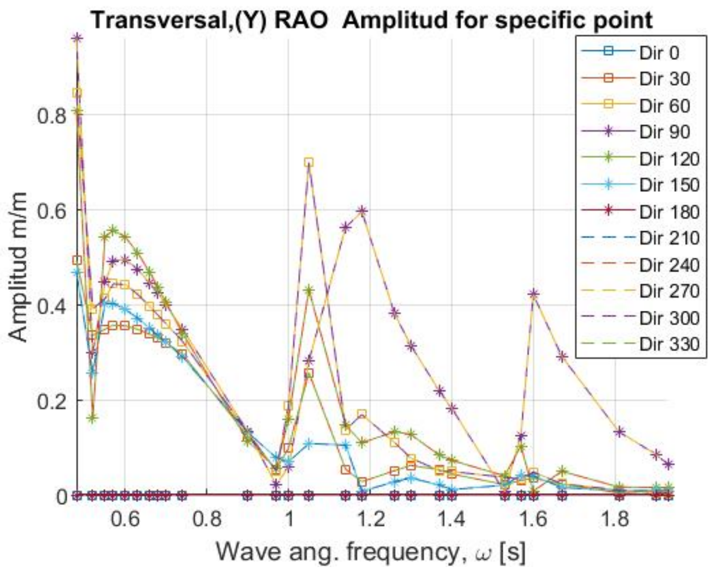


Figure 4.14: RAO for specific point, referred to Y axis, for WT1B

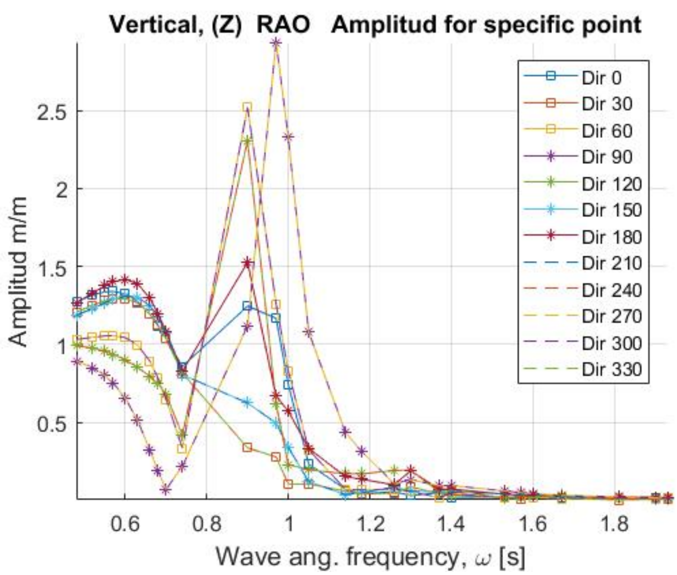


Figure 4.15: RAO for specific point, referred to Z axis, for WT1B

4.3.3 Response spectrums

The response spectrum is obtained to each heading angle, in the figure 4.16 an example for the Heading of 90 degrees and responses in X directions are shown.

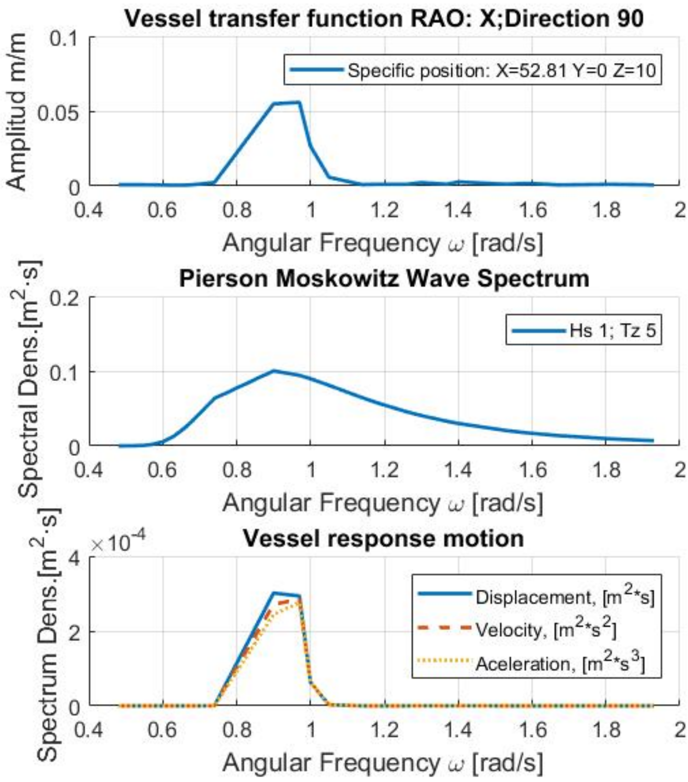


Figure 4.16: Procedure where RAO for specific point and PM wave spectrum are used to calculate Disp, Vel, and Acc. referred to X axis

It can be noticed that, for the above example the peak of the spectrum of the RAO and the Wave are around the same frequency, Which produce that the max amplitudes in the response spectra are aligned The maximum values for the Response spectra are:
$MPM_{Resp} = 0.0349$

$MPM_{velocities} = 0.0335$

$MPM_{accelerations} = 0.0322$

Another example is the RAO in the Y direction where for the same heading different peaks are presented, then response spectrum calculated give also 3 peaks, but the higher is where the wave spectrum has its peak.

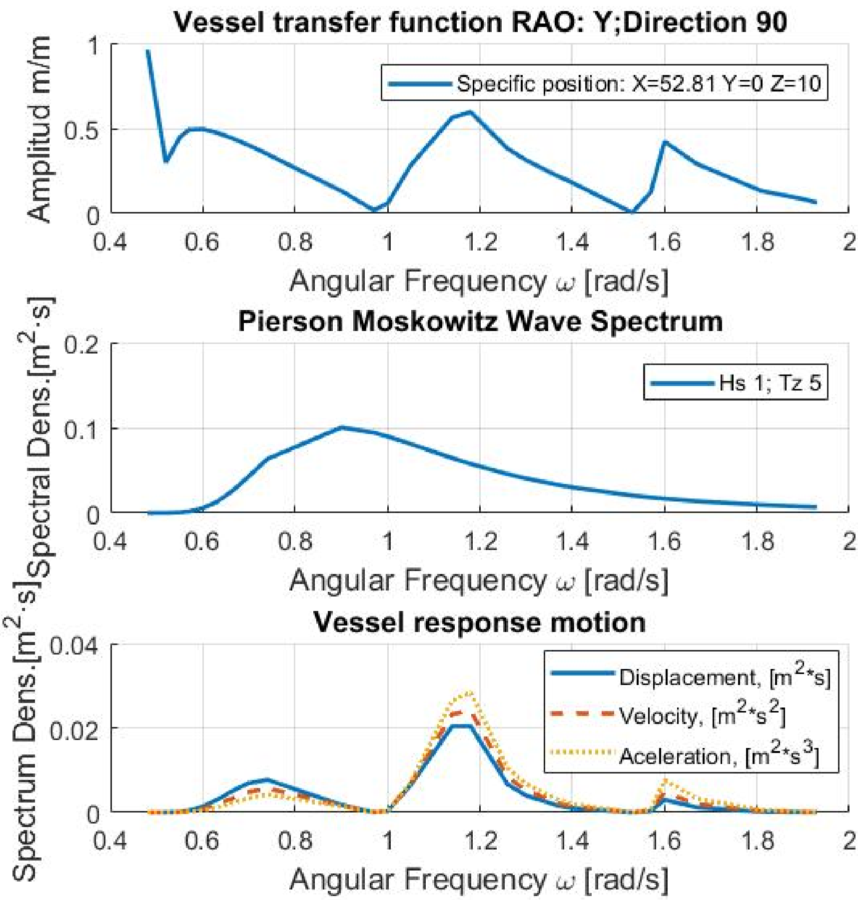


Figure 4.17: Procedure where RAO for specific point and PM wave spectrum are used to calculate Disp, Vel, and Acc. referred to Y axis

Also the max values are given, it can be seen that are bigger than the X values. $MPM_{Resp} = 0.3682$

$MPM_{velocities} = 0.3824$

$MPM_{accelerations} = 0.4075$

Special case is in the Z axis where a clear natural frequency can be exited at 1.3 ω, or a wave period of almost 5 seconds, aligned with the peak of the wave spectrum. Which also is around the value of 2 wave length per ship length, and one of the peak values of the scatter diagram, which gives a small motion but will be constant.

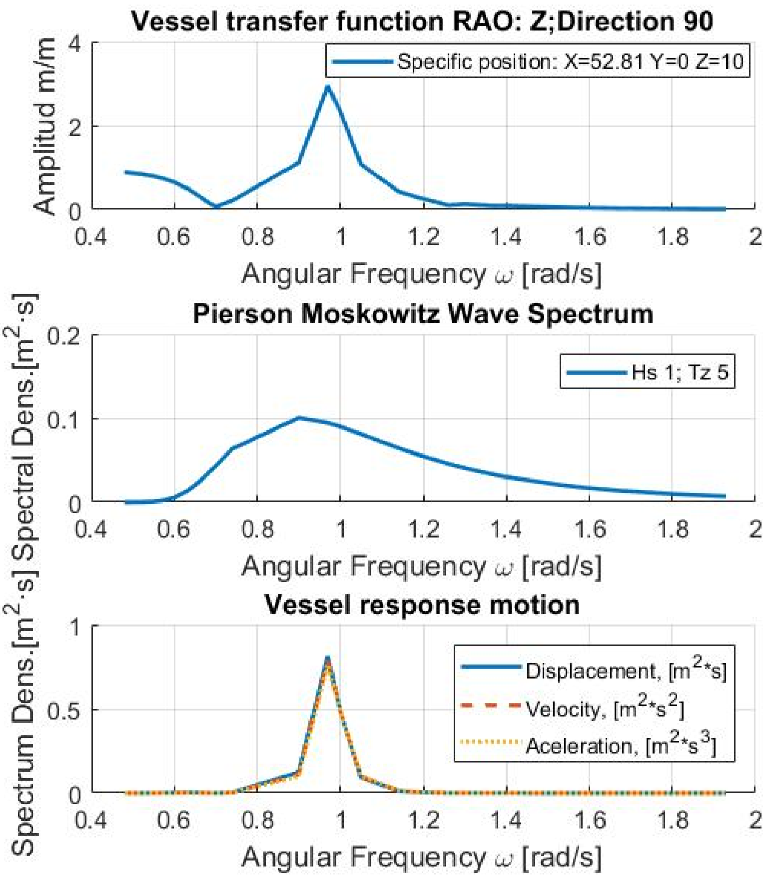


Figure 4.18: Procedure where RAO for specific point and PM wave spectrum are used to calculate Disp, Vel, and Acc. referred to Z axis

$MPM_{Resp} = 1.3121$

$MPM_{velocities} = 1.2916$

$MPM_{accelerations} = 1.2736$

4.3.4 Short term responses results: MPM; Displacements, Velocity and Accelerations results

The MPM values where obtained for each Tz and for each heading, the following figures shows the MPM for heading of 30 degrees and for each axis.

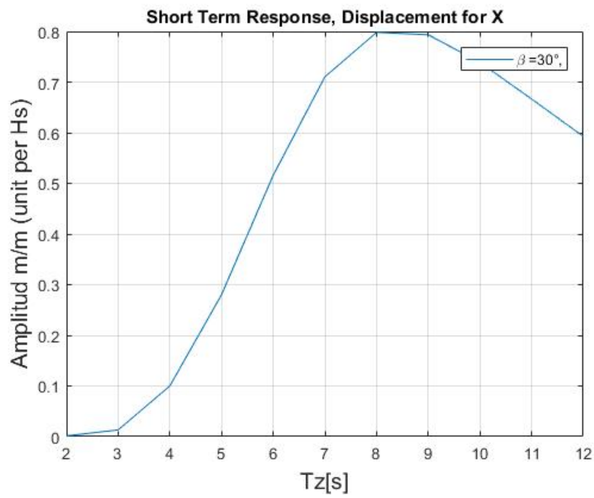


Figure 4.19: Displacement MPM amplitude for X axis

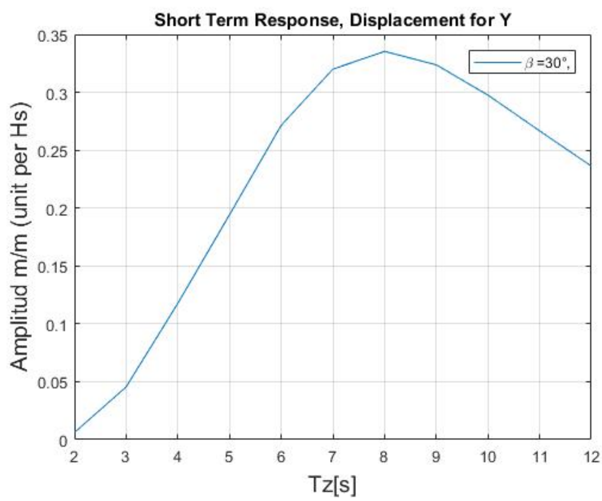


Figure 4.20: Displacement MPM amplitude for Y axis

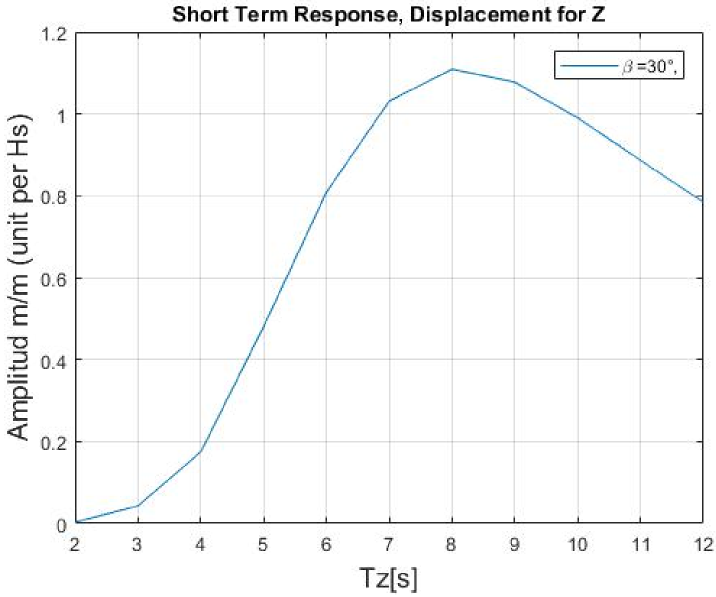


Figure 4.21: Displacement MPM amplitude for Z axis

Since the MPM curves are for each headings, axis, motion and specific point, an illustrative way to analyze them is by the use of polar plots, where the MPM are express, and the symmetries can be seen. One figure like the 4.22 is made for displacement, velocity and acceleration, and for each axis.

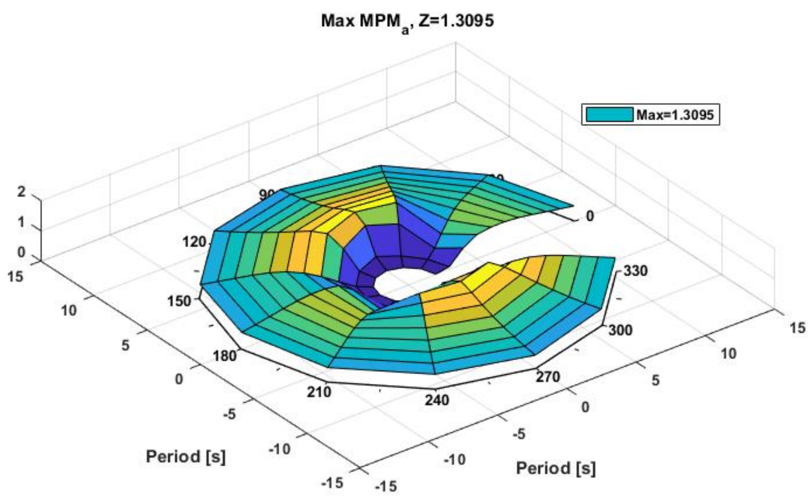


Figure 4.22: Acceleration on Z axis, unit per Hs, for WT1B

The next figure then is the final result of the dynamic analysis, where all the values of motions and axis are present for the specified point. It can be notice that for the X axis the values around 90 are almost zero, meanwhile for the Y axis happens at 0 and 180 degrees.

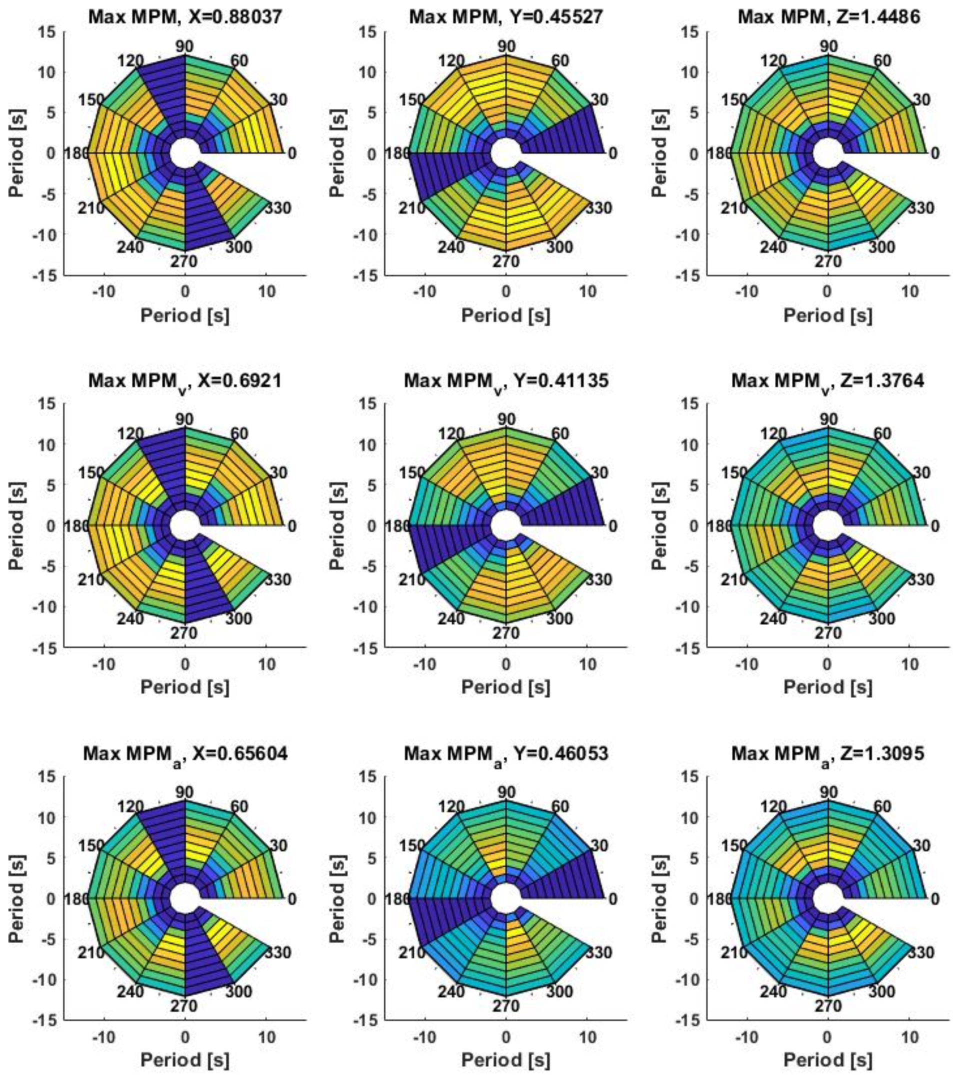


Figure 4.23: Polar plots for the specific point of WT1B

There are lot of point that can be of interest, for the objective of the analysis the specific points will cover Aft, Fwd, the waterline, at mid section max beam, the base of the WT towers 1 (the Fwd one) and the WT tower 4, as well as the COG of the nacelle for WT1 and WT4. The values in the following figure are given from the geometrical origin and for the waterplane origin where the motions are calculated.

					MPM					
		Location			Displacement			Acceleration		
No.	Points of Interest	x	y	z	x	y	z	x	y	z
1	Af	-70	0	18			*	*		*
2	Fw	62	0	18			*	*		*
3	M	0	30	18			*		*	
4	WL	-2.81	0	8	*	*	*	*	*	*
5	WT1B	50	0	18				*	*	*
6	WT1N	50	0	137				*	*	*
7	WT4B	-40	0	18				*	*	*
8	WT4N	-40	0	137				*	*	*

*Respect to the base line & midship, Geometry Origin [0,0,0]

					MPM					
		Location			Displacement			Acceleration		
No.	Points of Interest	x	y	z	x	y	z	x	y	z
1	Af	-67.19	0	10			*	*		*
2	Fw	64.81	0	10			*	*		*
3	M	2.81	30	10			*		*	
4	WL	0	0	0	*	*	*	*	*	*
5	WT1B	52.81	0	10				*	*	*
6	WT1N	52.81	0	129				*	*	*
7	WT4B	-37.19	0	10				*	*	*
8	WT4N	-37.19	0	129				*	*	*

*Respect to water plane & COF,Geometry Origin+[2.81,0,8]

Figure 4.24: Long term response.

4.3.5 Long term responses results

A long term result was calculated using POSTRESP. Even, the vessel will be changing its location and will be at service in good weather condition then the short term response is the one that will be more important for the scope of this report.

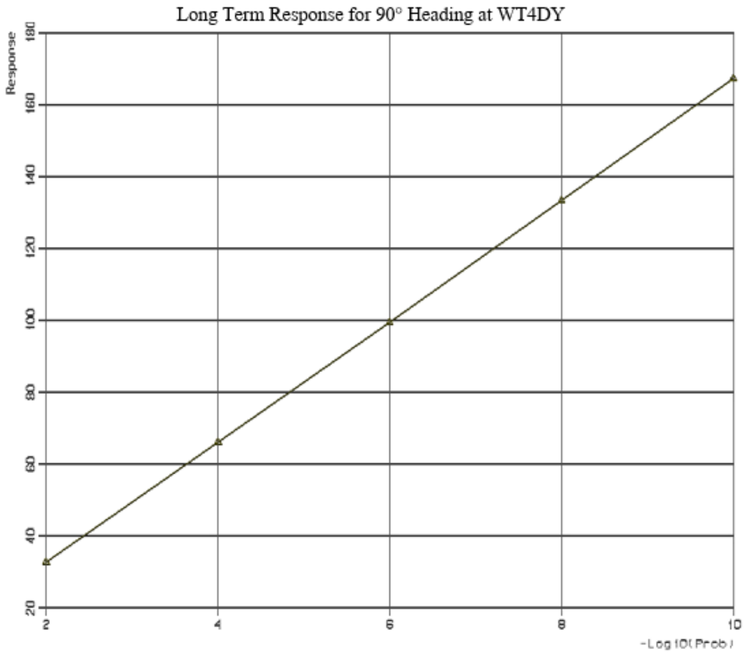


Figure 4.25: GZ Curves of the vessel.

Parameters used in long term distribution:
==
HEADING Prob Period Scale Threshold Slope ResSD NoIter

90.00 0.083 9.372E+00 6.915E+00 9.845E-01 2.370E-02 4
Response given probability of exceedance:
==
HEADING -LOG(Q)=2 -LOG(Q)=4 -LOG(Q)=6 -LOG(Q)=8 -LOG(Q)=10

90.00 3.262E+01 6.596E+01 9.956E+01 1.334E+02 1.673E+02
Response given return period in years:
==
HEADING Years=1 Years=5 Years=10 Years=50 Years=100

90.00 1.085E+02 1.203E+02 1.253E+02 1.372E+02 1.423E+02

4.4 Preliminary designs for the sea fastening of the wind turbine assemblies

A pair of simple preliminary design of a frame type sea-fastening was performed, meanwhile the structural loading conditions include have its focus on the tower, the equipment represent as an equipment and the sea fastening, where the max accelerations where applied. One was made of beam elements, which consist on a simple structure, and the second one a shell element connected from the structure to a jacket, that is meant to be mechanically removed when installation is in course.

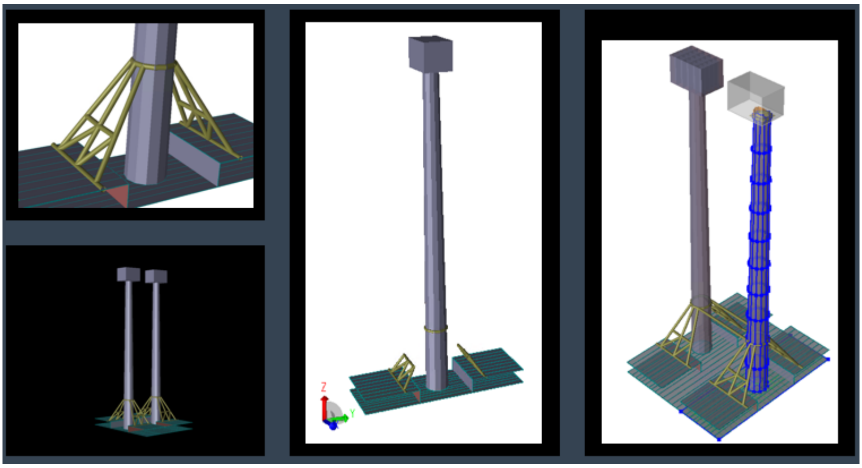


Figure 4.26: Preliminary design for the sea fastening

4.4.1 Structural analysis of the sea fastening

Deflection and Von-Mises Stress where obtained for the cases with and without sea-fastening.

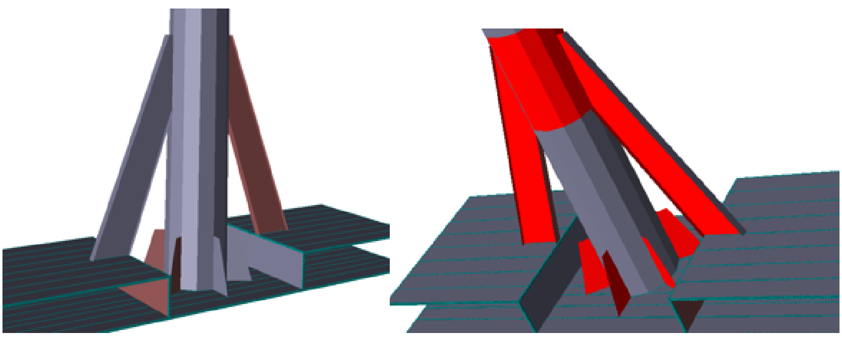


Figure 4.27: Analyses of the sea-fastening performance

Chapter 5

Results

5.1 Scope

This section includes the results from the steps commented in the last chapter.
Two loading conditions were taken into account, one that benefits stability but tends to a scenario with worst accelerations; and a condition that will reduce accelerations scenario but also decrease the stability capacity. The GZ curves of them can be seen, as well a comparison with a barge shape with same dimensions.

The Stability analysis was performed with HydroD, it was find sufficient for the wind turbine transportation. As well, the shape of the vessel was improved to stand the wind survival criteria.

Pierson Moskowitz Wave Spectrum was calculated for limits of the route parameters and of interest.
RAO's for six degrees of freedom were obtained by WAMIT and WADAM, this were compared and verified with MATLAB. An example of them are the figures above. RAO's for specific point of interest were created by coupling responses. Response spectrum were obtained for Short and Long Crested Sea. The accelerations at the base of the towers and at the nacelle were obtained, and applied on a Structural FEM model, being smaller than the default criteria for LRDF. Since the height of the WT, the accelerations at the nacelle are bigger than 0.3g for the worst scenario case, at short crested sea.

5.2 Results from hydro-static and hydrodynamic analyses

5.2.1 Intact stability analysis results

GZ curves

The worst case scenario with the center of gravity at deck and the scenario where the CG is above the CB, are shown in the following figure. A more realistic scenario, where the compartmentalizing is done, the structure defined and the ballast distributed, should give a value for stability between the two shown curves.

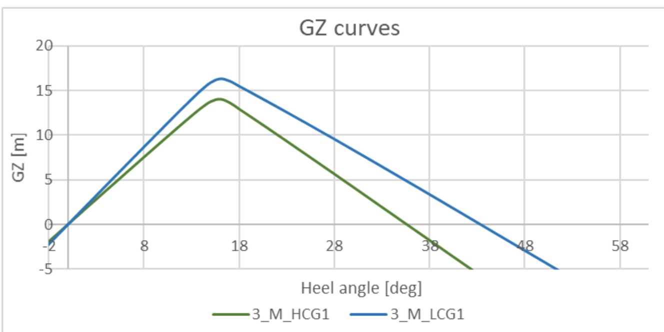


Figure 5.1: GZ Curves of the vessel.

Stability Criteria

Offshore supply vessels With Max. GZ under 30° (Offshore)	Stability criteria			Code IS part A, 2.2.1	Code IS part B, 2.4.5.2.1			Code IS part A, 2.2.1	Code IS part B, 2.4.5.2.2	Code IS part B, 2.4.5.2.3	Code IS part B, 2.4.5.2.4	Code IS, part B, 2.2.4.3	Code IS part B, 2.4.5.2.5	Code IS part A, 2.3.1.4	
				Area under GZ from 0° to 30 °	GZ-Area until max angle, if this is between 15 and 30°			Area under GZ from 0° to 40°	30-40 or 30-ϕ	Righting Arm GZ 30	Max Righting Arm Angle	The minimum range of stability: (by interpolation)	Metacentric Hight GM	The area **B** should be equal or bigger than area **A**	Angle of vanishing stability
Condition	Draft (m)	V Desp. (m³)	CGz (m)*	>0.055 m-rad 3.151 m-grad	0.055+0.001(30°-ϕMax) m-rad			>0.09 m-rad 5.157 m-grad	>0.03 m-rad 1.719 m-grad	>0.2 m	>15°	20° if L ≤100m 15° if L ≥150m	>0.15 m	B>A	-
Hi CGz	**8**	**16843**	**43.5**	**4.35**	0.069	**<**	**2.09**	**4.43**	**0.078**	**4.2**	**16**		**54.4**	**0.034**	**35.6**
Low CGz	**8**	**16843**	**35.12**	**5.47**	0.069	**<**	**2.41**	**6.39**	**0.92**	**8.3**	**16**		**62.7**	**1.58**	**43.37**

Blue	General IS criteria
Yellow	Offshore suply Vessels
Pink	Pontoons

*Values from baseline

Figure 5.2: GZ Curves of the vessel.

The stability criteria designed to cover most of the values needed to ensure a good stability where satisfied.

Moment for GZ curves and Survival wind condition

The righting moment was calculated for both loading conditions and compared with the moment for survival condition for the wind speed of 36 m/s + 40 percent. The dynamic angle as is defined in the rules [5], is where the area of the righting angle does not supersedes the heeling angle plus 40 percent, that in this case is at 45 degrees and 60 degrees for the Hi COG condition and 60 for the Low COG conditions respectively.

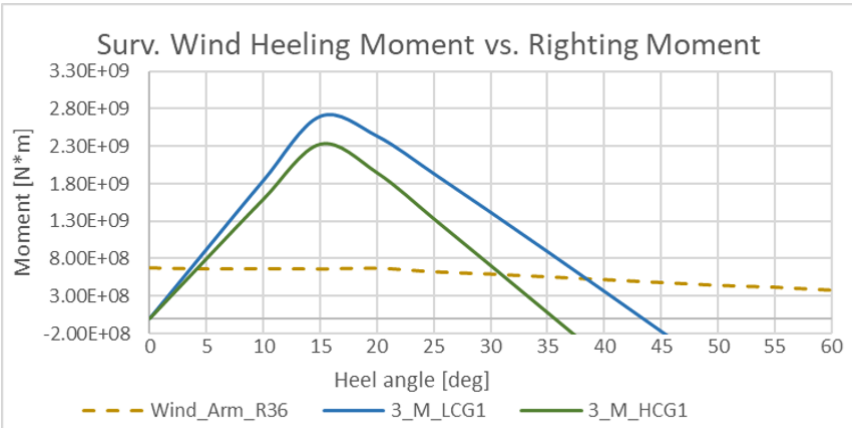


Figure 5.3: GZ Curves of the vessel.

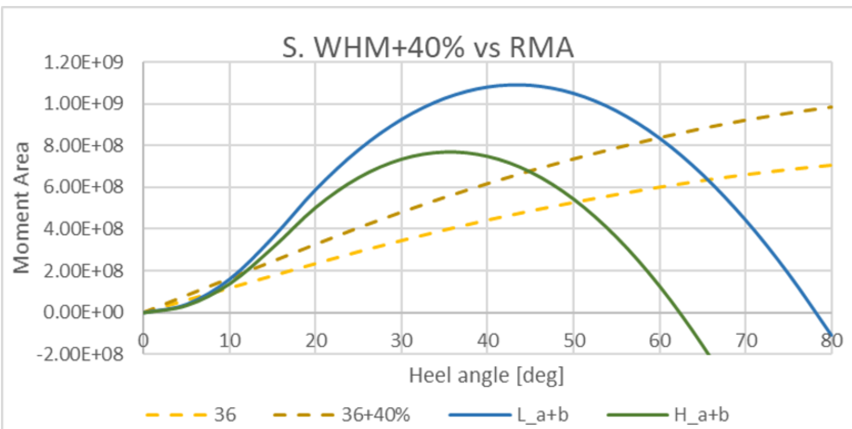


Figure 5.4: GZ Curves of the vessel.

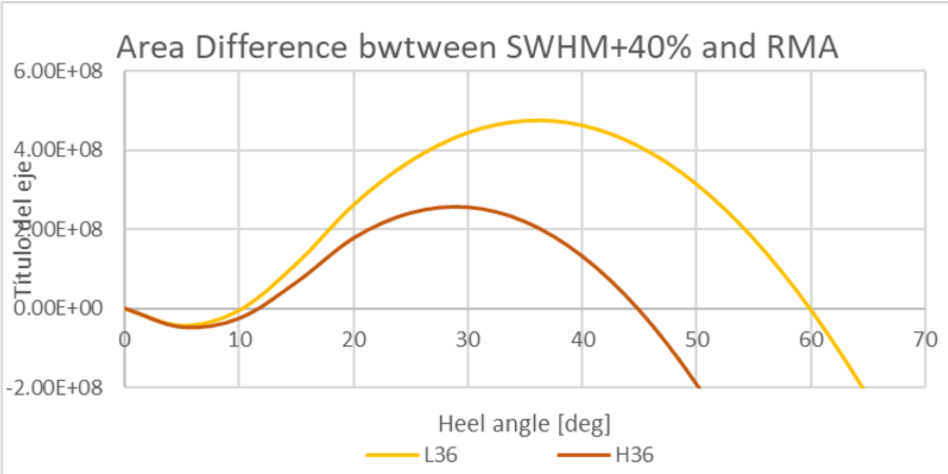


Figure 5.5: GZ Curves of the vessel.

5.2.2 Dynamic Response Analyses Results

In the following pages the MPM for each of the point of interesting are shown. The symmetry helps to ensure that they are correct, and some of the values where compared with SESAM. Each one have the max MPM for each motion. Those values where used as the input for the structural analysis.

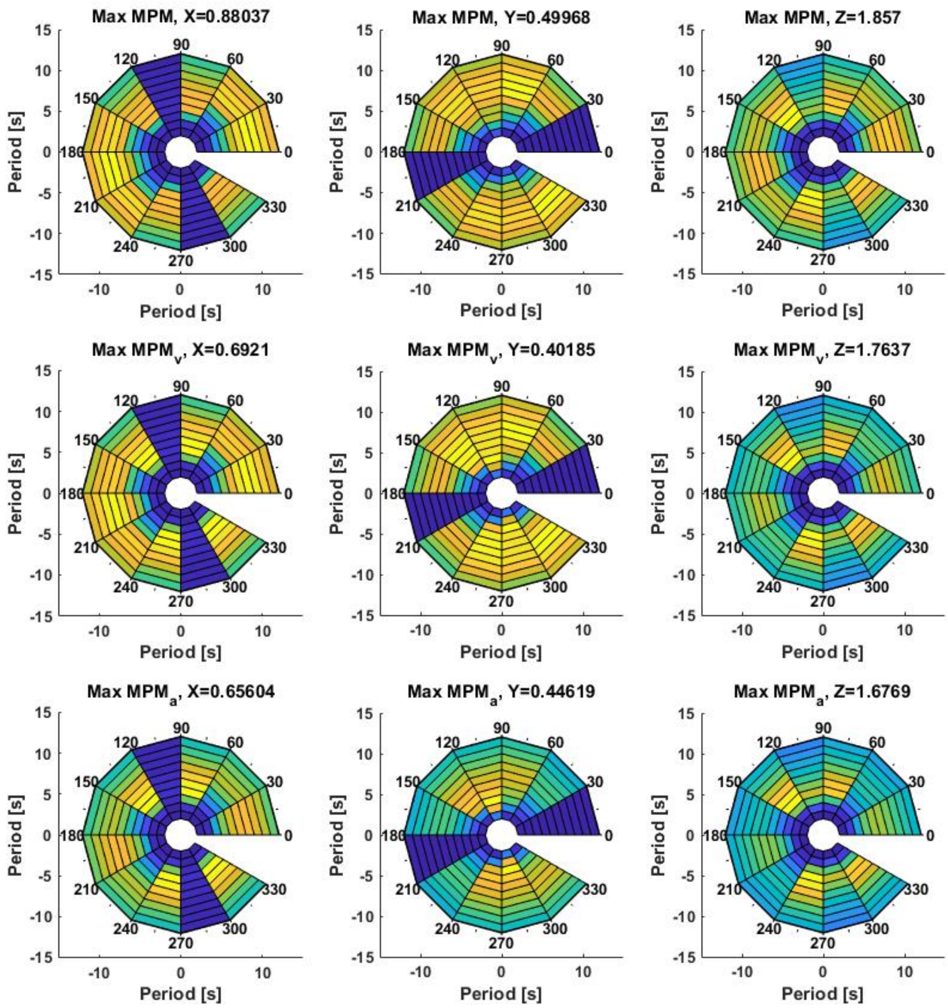


Figure 5.6: Max MPMs, AF

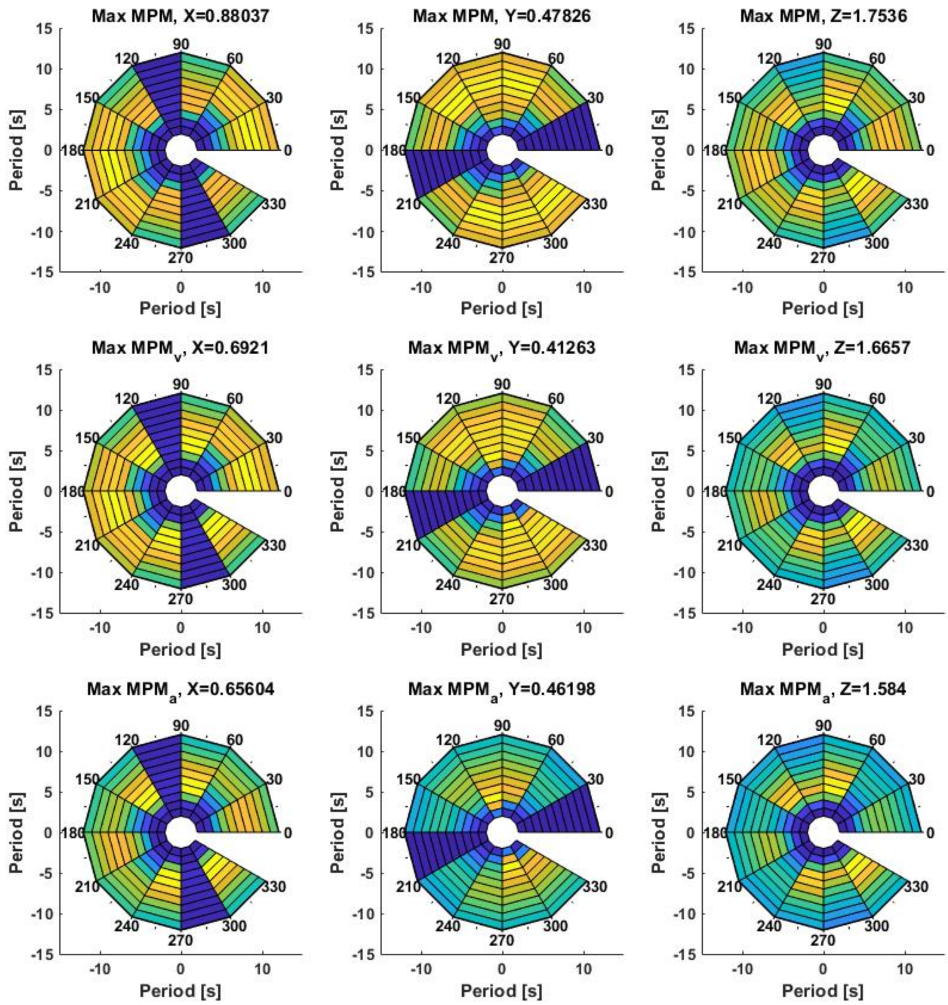


Figure 5.7: Max MPMs, Fw

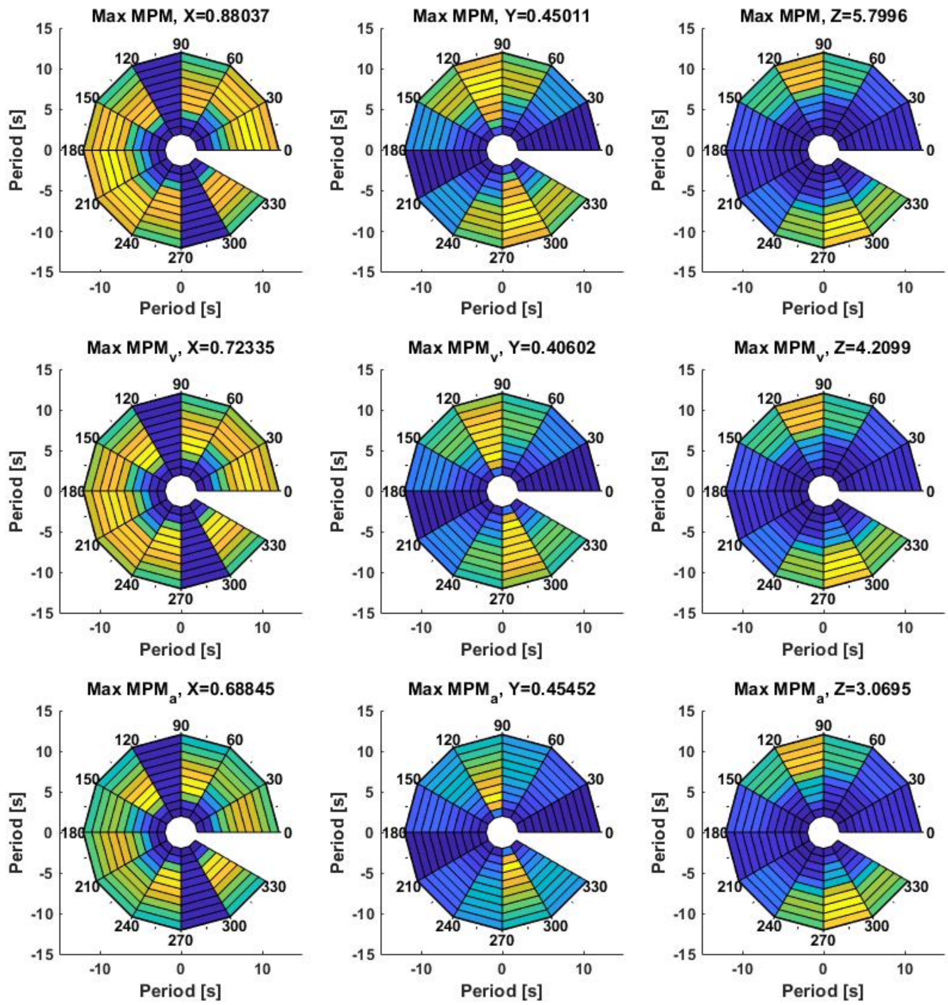


Figure 5.8: Max MPMs, M

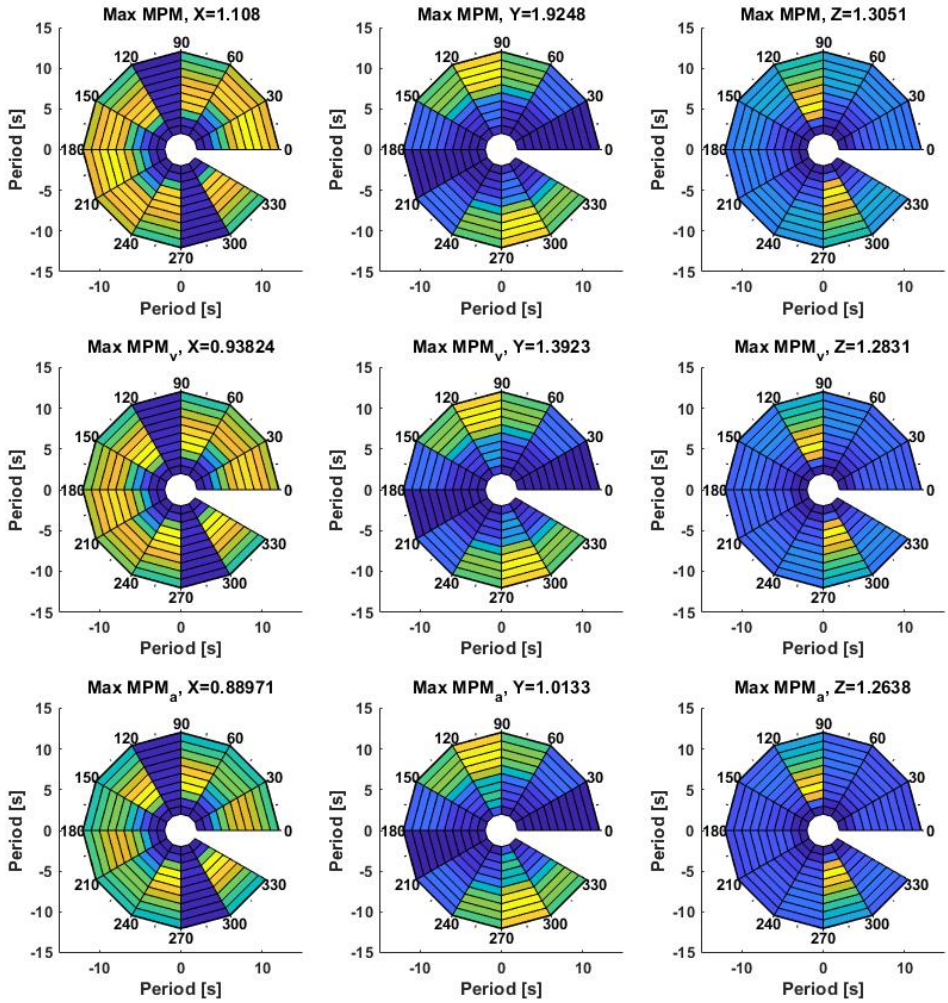


Figure 5.9: Max MPMs, WL

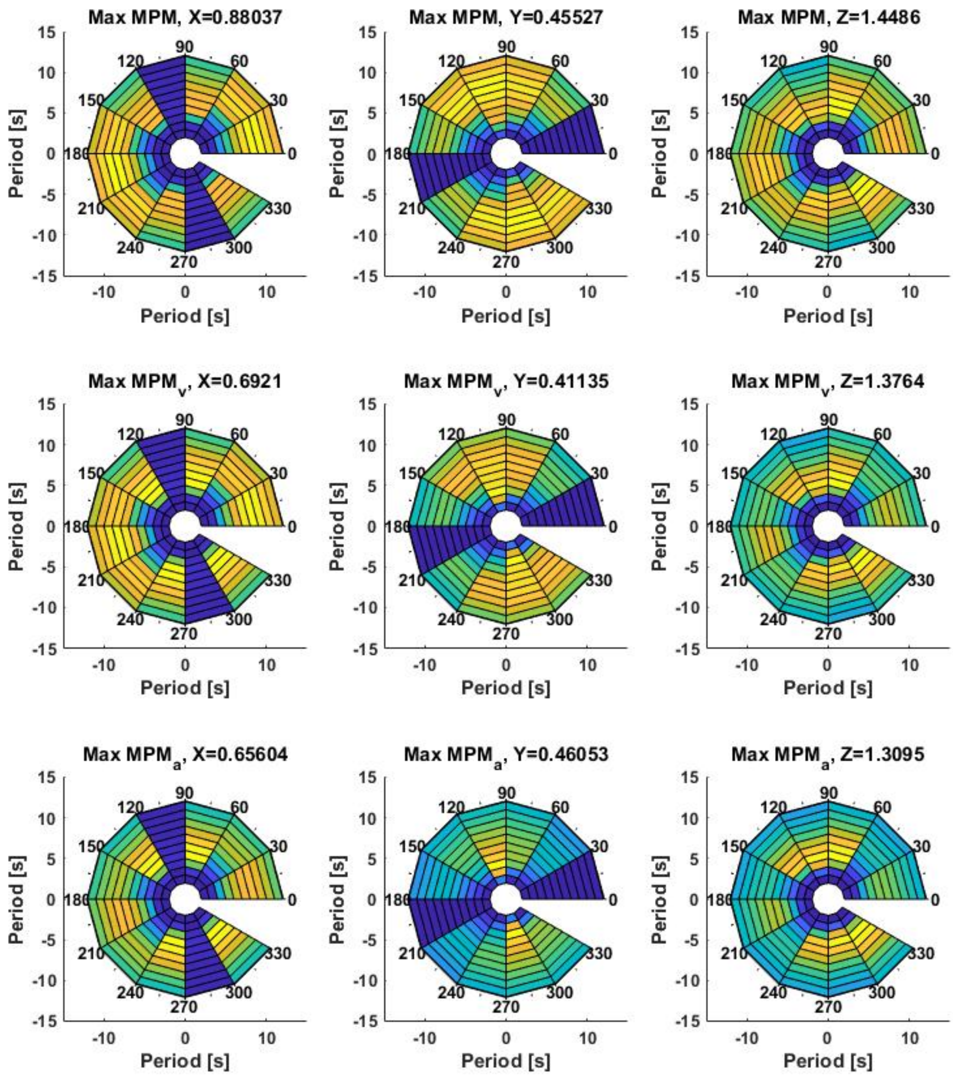


Figure 5.10: Max MPMs, WT1B

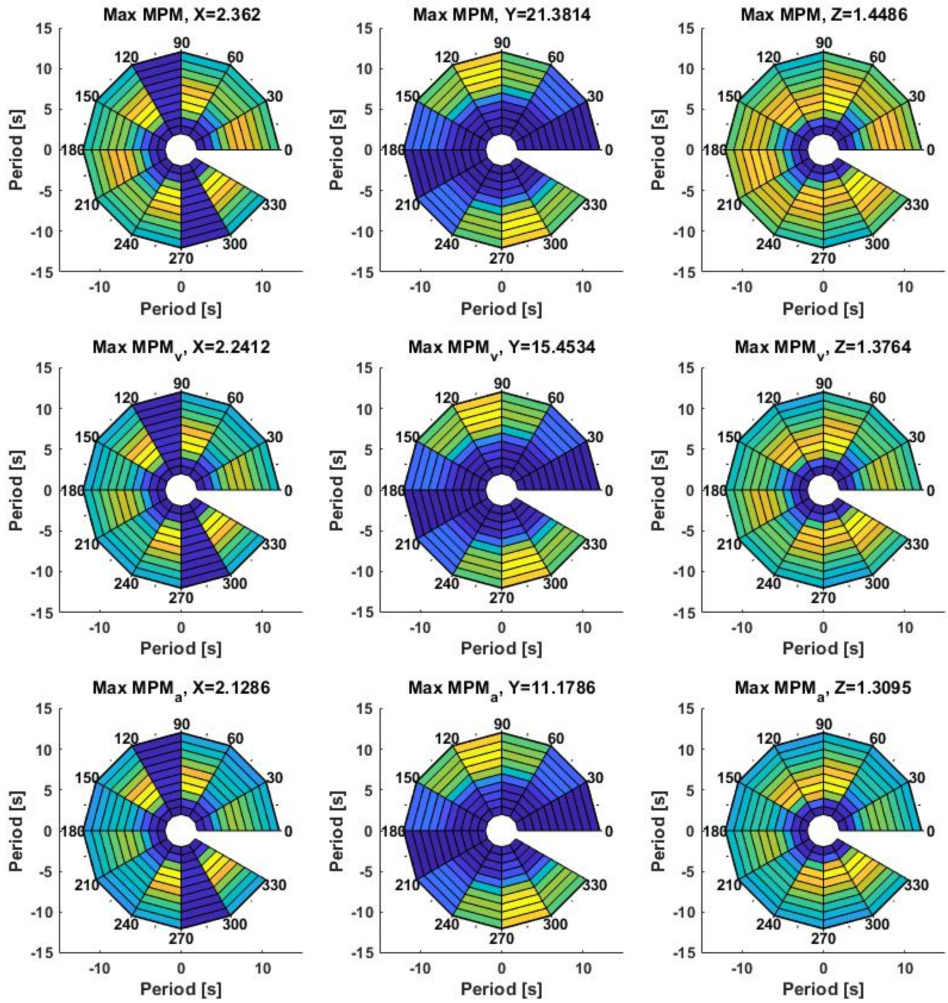


Figure 5.11: Max MPMs, WT1N

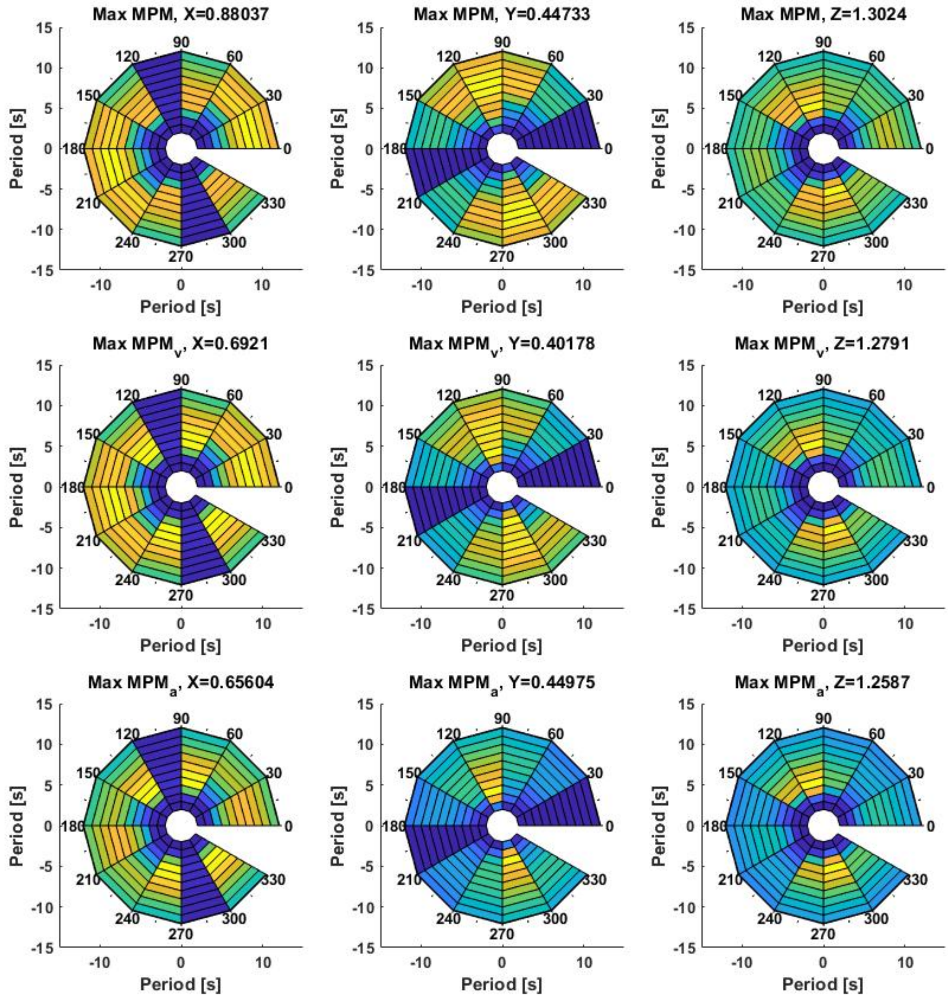


Figure 5.12: Max MPMs, WT4B

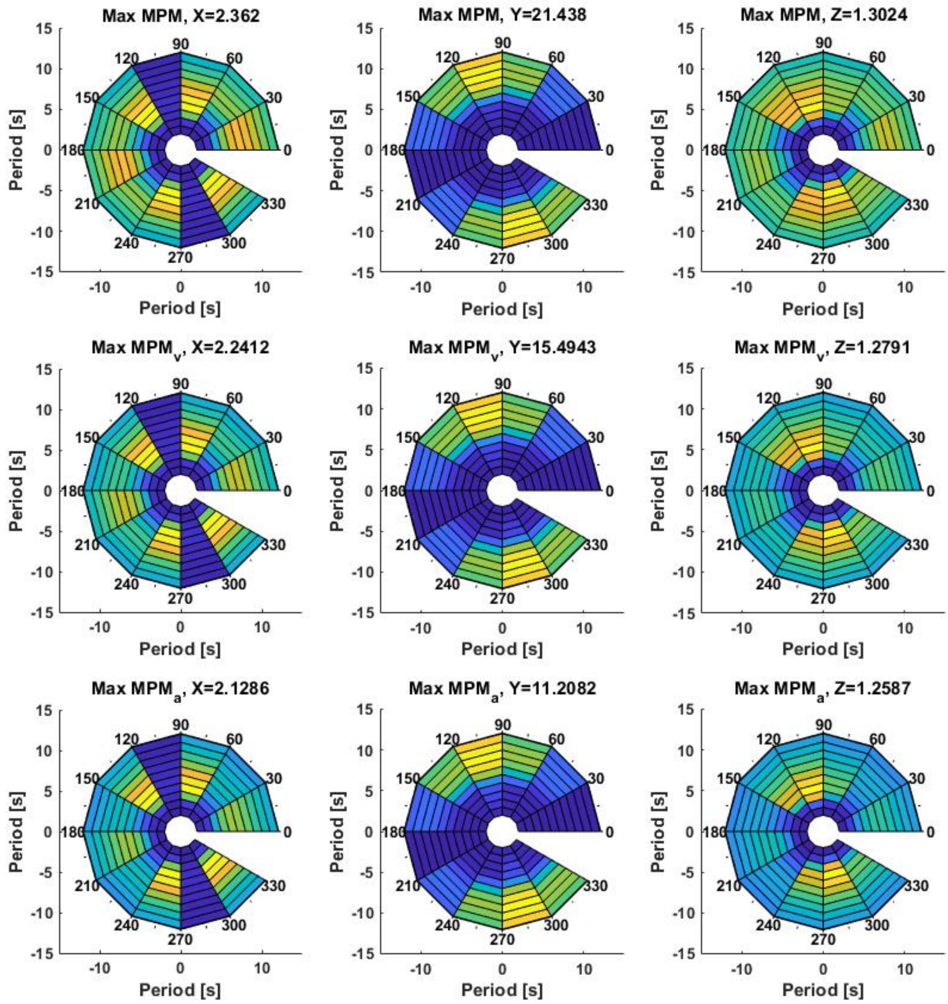


Figure 5.13: Max MPMs, WT4N

Finally, the resume of the obtain max values is resumed in the following chart. It can be seen that the maximum acceleration for some point exceed the 0.3g that represents the limit for the design of the nacelle.

MPM

No.	Points of Interest	Location			Displacement			Acceleration			Acceleration/g		
		x	y	z	x	y	z	x	y	z	x	y	z
1	Af	-67.19	0	10	0.88	0.50	1.85	0.65	0.44	1.68	0.07	0.04	0.17
2	Fw	64.81	0	10	0.88	0.47	1.74	0.66	0.46	1.57	0.07	0.05	0.16
3	M	2.81	30	10	0.88	0.45	5.80	0.69	0.45	3.07	0.07	0.05	0.31
4	WL	0	0	0	1.11	1.92	1.31	0.89	1.01	1.26	0.09	0.10	0.13
5	WT1B	52.81	0	10	0.88	0.46	1.45	0.66	0.46	1.31	0.07	0.05	0.13
6	WT1N	52.81	0	129	2.36	21.38	1.45	2.13	11.18	1.30	0.22	1.14	0.13
7	WT4B	-37.19	0	10	0.88	0.45	1.30	0.66	0.45	1.26	0.07	0.05	0.13
8	WT4N	-37.19	0	129	2.36	21.44	1.30	2.13	11.21	1.25	0.22	1.14	0.13
	max				2.36	21.44	5.80	2.13	11.21	3.07	0.22	1.14	0.31

Figure 5.14: General Max MPMs

5.3 Results from preliminary design of the sea-fastening structure

Verification of Results. In order to know if we have correctly performed the analysis or if it represents reality well, we must have an idea of how it will respond. For example, if after applying a significant load in a certain area, no change has occurred, it can be assumed that the model should be improved, or that the system present an error in the application of the loads, the meshing is not appropriate , etc. Once studied and verified that the model has worked correctly, the Finite Element Analysis has been carried out as mentioned in the previous chapter. The results are obtained through the corresponding post-processing software, which in this case is Xtract, being only a visualizer of the results analyzed by Sestra.

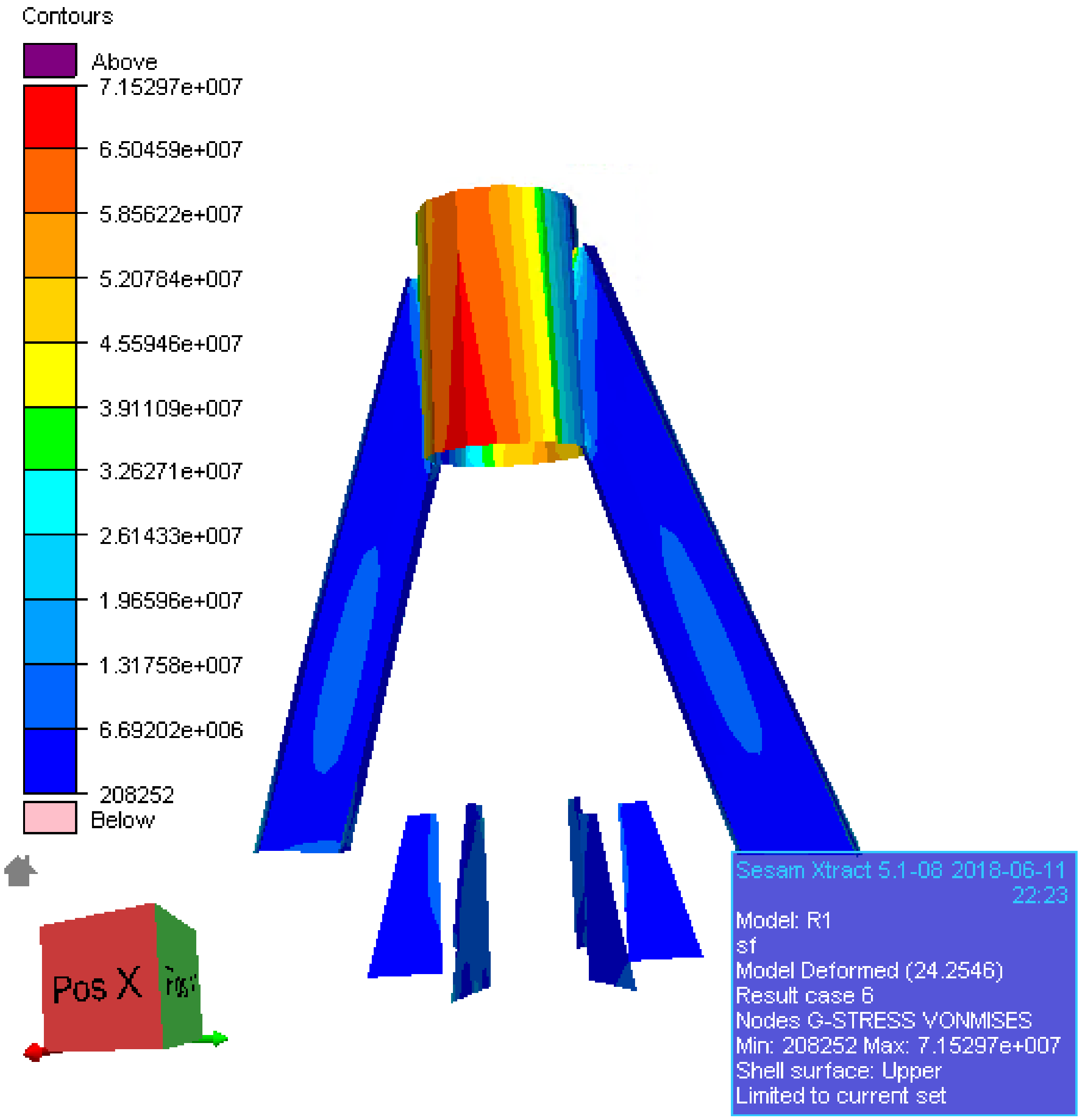


Figure 5.15: Von misses for shell sea-fastening, max acceleration in Y

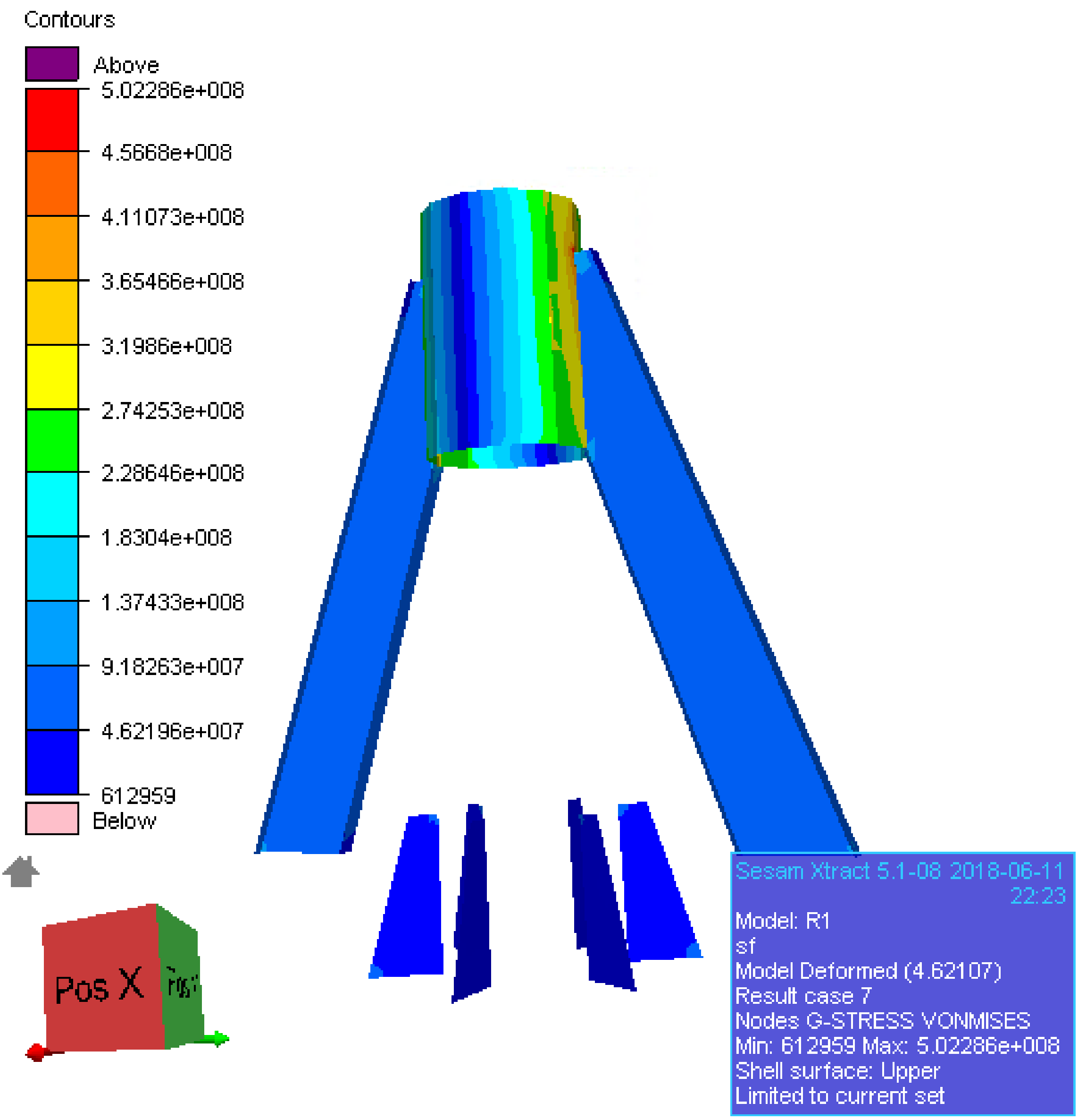


Figure 5.16: Von misses for shell sea-fastening, max acceleration in Y

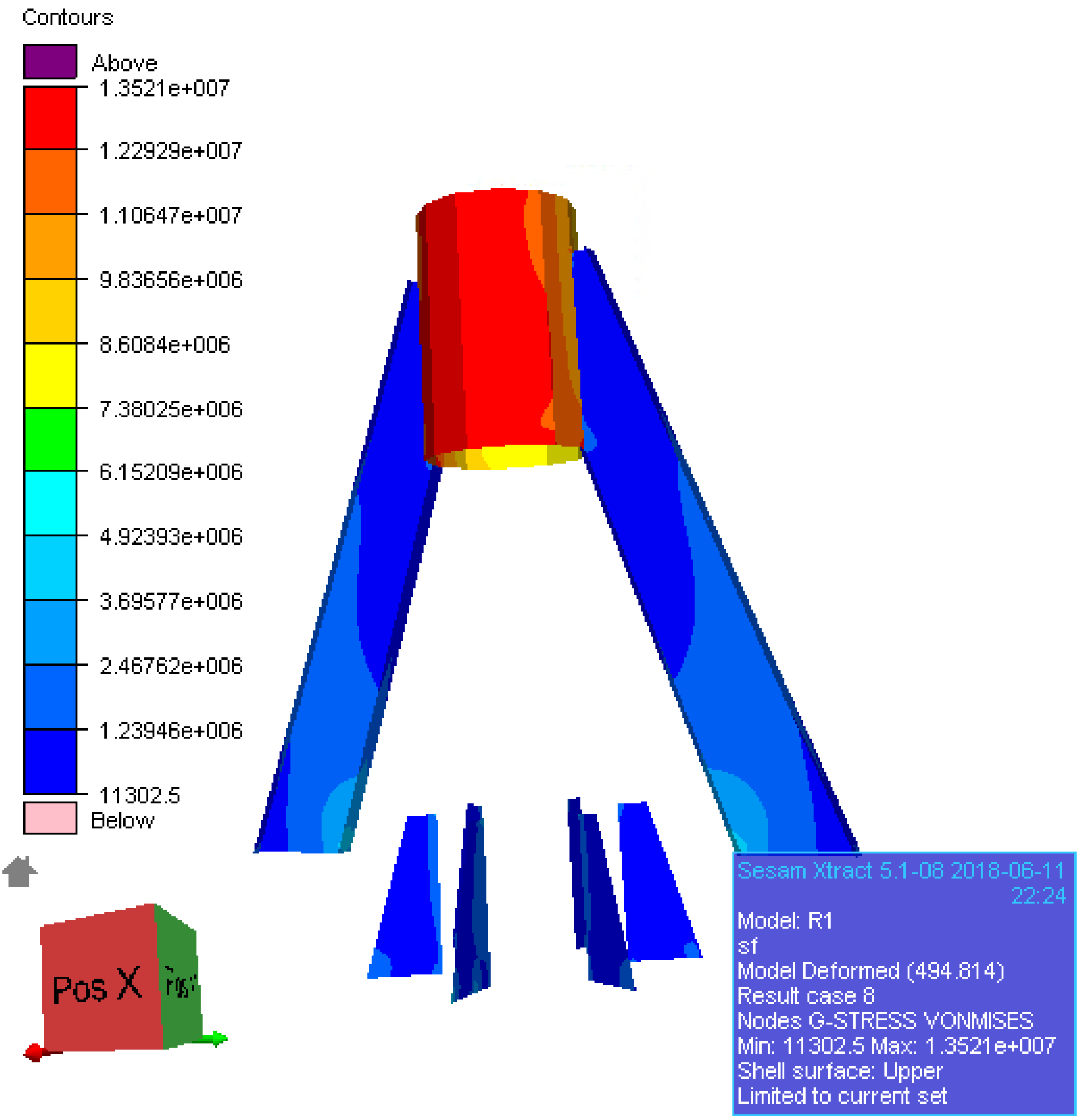


Figure 5.17: Von misses for shell sea-fastening, max acceleration in Y

Chapter 6

Discussion

6.1 Scope

The next chapter contains the discussion about the validity of the results obtained, comparing what was done and, if possible, how best results were obtained.

6.1.1 Numerical Model

The model panel is where the importance of the hydrodynamic analysis is concentrated and, in the tower-deck-seafastening system for the structural one.

The personal knowledge of the software simplified the modelling procedure since by knowing the way it works a file could be made in which the forms of the helmet were correctly indicated in a smooth manner.

The direct recommendations, as well as webinars available by DNVGL members, such as the use of the symmetry of the model panel to reduce considerably the modelling time and the criteria to be able to select certain initial parameters to benefit the obtained result.

Another important point when modeling is that being a large vessel, reaching a mesh where the length of the wave corresponds to what is required to be properly analyzed at high frequencies is more complex, even as could be checked in the quality check the frequencies used and for the vessel were sufficient since it was possible to have values that converged when passing the quantity of four elements per wavelength.

There were some simplifications that were made to perform the analysis, like the structure of the vessel is still not defined, therefore the compartmentation and the place for the different equipment's and ballast. This led to the mass model used to be specified directly and to be Concentrate on the center of gravity which contributes to the results obtained are not as accurate as if you had the information at a more advanced stage of design. By placing the mass in a single specified center, the weight cannot be considered as distributed, so the software does not allow the vessel to be discretized along the length and therefore obtain a diagram of the flexing moments.

The part in which less detail is found in the model is in that of the wind turbines, since a gross simplification of the nacelle, changing the initial cylindrical shape for one of the rectangular prism since in this way the moment produced by wind. And since the Blades will not require moving as it would be in a service analysis for the WT or even in some stage of installation, the simplification of the same can be considered appropriate.

6.1.2 Loading conditions

The loading conditions, as described above, were selected, so that they represent the extremes for the case of vessel stability, with the center of gravity on deck, as suggested by the IS code for the section of pontoons, since the stability of these vessels that have a ratio of beam length relatively less than that of a generic monocoque have much greater overall stability than the latter. In turn, the analysis was performed with the center of gravity of the vessel a little above the center of buoyancy, which represents a less conservative but more realistic case. Having these two reference points for this stage of the design you can have a good idea of the behavior that the vessel will have and even if it can be considered with an over design. Therefore, it is considered that the loading conditions are adequate.

6.1.3 Stability analysis

As you can see in the chapter of the results, the stability of the vessel is sufficient as expected from a vessel of this type. Even with an area exposed to the wind that generates an extremely long heeling arm, compared to any vessel in general, it can meet the requirements for survival condition.

The selection of the stability criteria for a vessel of this class, its dimensions, type of load and speed, do not exist properly as it is a vessel of a unique type. Even so, the criteria were selected with a wide variety of parameters, complying with what would be expected from the general criteria, where it should be remembered that catamaran or pontoon-type vessels do not meet the criterion of maximum gz over the 25 degrees of heel, but compensated with a large area under GZ prior to 10 degrees. Additional criteria were also met that could be for offshore supply vessels, and for pontoons, which covers a range of criteria more than sufficient to comply with the stability guidelines that may be applied.

For the calculation of the heeling moments wind, was taken into consideration only of the direction perpendicular to the vessel since it is normally the most critical situation. Different wind angles should be considered for a more advanced design stage, however, because of the capacity that is shown from this wind direction it can be assumed that there will be no problem from any angle.

6.1.4 Hydrodynamic process

The selection of the criteria prior to the dynamic analysis to obtain the RAO of the vessel could be considered the most complex part of the work, not only because the amount of information of catamarans is not as coarse as that which exists of monohulls. A correct selection of the directions, the influence of the route, the periods of the wave as well as a correct distribution of the frequencies.

The use of the values generated in WAMIT format instead of taking the values produced by WADAM, produces that the MPM values for Tz higher are also higher. Which leads to continue with the conservative perspective that has been carried out throughout the work.

It is worth mentioning that an analysis to see if the reduction of irregular frequencies generated some impact on the obtained motions, being that the catamaran's mistresses produce reactions among themselves, as seen in the result of the added mass.

Although an analysis was made for long term statistics for the heading of 90 degrees, the fact that it is a structure that is in motion, in a specific route and that is assumed to sail only with good weather conditions, produces that the short term be in this case the most important to obtain, for all angles and Tz. In the case of fixed offshore structures, the analysis by long term is the most important since it cannot move from the site.

6.1.5 Structural design

The sea-fastening design corresponds to one of the most used systems in the industry since, by means of reinforcements, most of the elements of wind turbines are transported.

The design seeks to reduce the movements that will occur in the WT because the weight of the rotor and the height it is great influences the efforts that the structures of the vessel, sea-fastening and the same turbine will have to endure. Reducing these efforts helps the WT achieve better performance and reduce the risk of short-term or long-term damage to it. The use of beam type elements does not contribute to a better analysis, however, it allows a preliminary design of the sea fastening in an efficient way since it can be known as the reaction to different designs of the support structure. In addition to having made the addition of the rotor by means of subsets and prismatic equipment provides an interesting perspective on how it is distributed loads in the tower. For the case of the shell element simplified sea-fastening, prove to not be enough strong for the accelerations presented. The addition of a strip model to ad roll damping could be the difference.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The investment in the wind sector is increasing. There is going to be a gap between the energy that is needed and the one that is being generated if we continue using the same resources in the same way as in the past decades. A combination of resources will be needed and the environment has a need of using the ones that produce less pollution. Wind energy is one of the measures that are being used to affront the climate change.

There are several designs and methods trying to find ways to reduce the cost of any stage for wind energy production. In particular floating offshore wind turbines farm is just starting to be developed and seems to be a increment of them in the next years. Big floating farms are being planned and a better way to deliver the WT to site is needed. Therefore, designs like this are needed.

By performing a dynamic analysis, accurate accelerations can be obtained. This entails a reduction in risk and an increase in efficiency for all marine operations and therefore a reduction in costs.

Even than lot of conservative approach where taken into account, long crested sea, coarse shape for wind turbine, worst center of gravity for the vessel, the general performance of the vessel is acceptable for most of the conditions. So, is a good base for a proper detail design in the short term future.

Non conservative analyses for systems should be implemented together with anti roll systems to reduce the accelerations, since, they are more than 0.3g of accelerations, which is more than the tolerated for the design of the WT machinery. Is understandable for the specified WT heights and weights.

The sea-fastening could be sufficient if the accelerations can be lowered, by a not so conservative approach and a better damping coefficients.

7.2 Future Work

Since the present work is directed to a preliminary design there is lot of thing to add. Even the most important ones will be listed.

- Compartmentalizing of the vessel.
- Structure and Equipment's design.
- Stability analisis for damage condition
- Wind heeling analisis for different azimuth angles
- Time domain simulation for transportation
- Shell element seafastening design, using the acelerations finded douring the thesis.
- WT load-out system.
- Roll damping analyses and the use of a strip model should be performed. This can reduce the accelerations that result to be higher than expected to some specific parameters.

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Appendix A

Matlab Codes

A.1 Code 1- short term

```
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++
%%                            Master THesis
+
%
+
%Student: JORGE LUIS RANGEL VALDES
% Supervisors: Zen Gao, Yanlin Shao & Zhiyu Jiang
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++
%% Calculate the short-term responses for a Wind Carrier
Catamaran Vessel
%                               May 05, 2018
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++
%  Include estimation of motions, velocities and
accelerations
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++
% Reference code: ZHJ, (2017)
% References:       F,p.; Sea Loads
%                   Faltinsen
%
%                   N,p.; Ship Operations - Engineering
Analyses and Guidance,
%                   Ulrik Dam Nielsen
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++
% Cleaning & format comands
clear
close all
clc
format compact
%----------------------------------------------------------
--
%  Index:
%   +Input parameters
%   +Parameters before calculating
%   +RAO manipulation
%   +Calculate the RAO for the user-specified point
%   +Short-term response in the freq. domain
%----------------------------------------------------------
--
%Body: Wind Carrier Catamaran Type Vessel

%User inputs:
      % path & name for results out folder,
      % WAMIT5S_4 file(RAO results from WAMIT),
      % WAMIT5S.out file(results from WAMIT),
```

```
        % Point of interest on catamaran
        % interested wave headings data,
        % zero-crossing period data
        % range & time reference data (3-hour)

%output:
        % short-term relative motion responses (at path
folder)

%Toolbox:
        % WAFO toolbox
          initwafo;
          clc
%Functions:
        % - cumint3
%--------------Constants---------------------------%

rad2deg=180/pi;
deg2rad=pi/180;
n_dof=6; %total degrees of freedom
gaxis=3; % x,y,z global axis

%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%
%% +++++++++++++++++++++++++ Input parameters
+++++++++++++++++++++++++++++%
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%

heading=(0:30:330);
Tz = 2:1:12;  %upcrossing period (sec)

InputFile='C:\Users\jlrvn\Desktop\Final\WadamRun_M_H_1\WAMI
T_5S.4';  %RAO results from WAMIT
fname='C:\Users\jlrvn\Desktop\Final\WadamRun_M_H_1\WAMIT_5S
.out';   % result from WAMIT

pt_catamaran=[-37.19 0 10]; %point position on Catamaran
18(10) or 137(129)

WaveHeadInd = 1; % index of the wave heading for which to
plot everything
Wadfname =
'C:\Users\jlrvn\Desktop\Final\WadamRun_M_H_1\WADAM1.LIS';

path='C:\Users\jlrvn\Dropbox\NTNU\Thesis\General\Short';
%Output folder Location
OutFolder='CASE1'; % Output folder
```

```
  Hs =0.5:0.5:12.5;

% Tp>5*sqrt(Hm0) || Tp<3.6*sqrt(Hm0);
Hours=200;%876000;%0.05; %reference time period [h]


%parameter of JONSWAP:
gamma=3.02; % Peakedness factor determines the concentraton
of the spectrum
            %   on the peak frequency,  1 <= gamma <= 7.
            %   (default depending on Hm0, Tp)

sa=0.07; sb=0.09; %spectral width parameters
AA=-1; %normalization factor used when gamma>1, (default -
1)

% Plots, --------- 0 or 1 (1, plot; 0, do not plot)-----

Plot_RAO            =0; % Catamaran RAO plot
Plot_phase          =0; % Phase angle
Plot_RAO_specific   =0; % RAO for specific point plot
Plot_phase_specific =0; % Phase angle for specific point
plot
Plot_wave_spectrum  =0; % Spectrum plot
Plot_S_Response     =0; % Response for specific point plot
PlotMPM             =1; %Polar plot of MPM for each heading
and period per unit wave
%--------------end of input parameters

%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%
%% +++++++++++ Parameters found from inputs before
calculating +++++++++++%
%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%

% Period=zeros(48,1);
% Periodwave=1./((omega)./(2*pi));
Tref=Hours*3600;
Plotflag=Plot_wave_spectrum;
% freq=(1./Tz); % Hz, descending
% w=freq*2*pi;% radians/s
% x_new=w';



Dir=zeros(length(heading),1);
RAO=cell(n_dof,1); % matrix
```

```
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%



fid = fopen(Wadfname);
A = textscan(fid,'%s','Delimiter','\n');
Wdata = A{1};

n=0;
ii = 1;
found = 0;
while ii<length(Wdata) && found == 0
    k = strfind(Wdata(ii), 'ENVIRONMENTAL DATA:');
    if ~isempty(k{1})
        n = ii;
        found = 1;
        C = textscan(Wdata{ii+3},'%s %s %s %f %s');
        waterdepth = C{4};
        C = textscan(Wdata{ii+4},'%s %s %s %s %s %f ');
        numwavelengths = C{6};
        C = textscan(Wdata{ii+5},'%s %s %s %s %s %f ');
        numheadangles = C{6};
        WaveDat = zeros(numheadangles,numwavelengths,5);
        for jj = 1:numheadangles
        for kk = 1:numwavelengths
            WaveDat(jj,kk,:) = str2num(Wdata{ii+kk+12});
        end
        end
    end
    ii = ii+1;
end
WavePeriodd=(WaveDat(1,:,4))';
WaveOmega=(WaveDat(1,:,5))';
ii = n;
found = 0;
while ii<length(Wdata) && found == 0
    k = strfind(Wdata(ii), 'THE OUTPUT IS NON-
DIMENSIONALIZED USING');
    if ~isempty(k{1})
        n = ii;
        found = 1;
         C = textscan(Wdata{ii+8},'%s %s %f');
         RO   =  C{3};
         C = textscan(Wdata{ii+9},'%s %s %f');
         G   =  C{3};
         C = textscan(Wdata{ii+10},'%s %s %f');
```

```
        VOL   =  C{3};
        C = textscan(Wdata{ii+11},'%s %s %f');
        L   =  C{3} ;
        C = textscan(Wdata{ii+12},'%s %s %f');
        WA   =  C{3} ;
    end
    ii = ii+1;
end



%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%
%% ++++++++++++ Post process, RAO manipulation section
+++++++++++++++++++%
%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%

% Post process the wamit.out and wamit.4 RAO data.

% Read input file WAMIT_5S.out
fid = fopen(fname);
if fid~=-1
A = textscan(fid,'%s','Delimiter','\n');
data = A{1};
else
    disp(['no such file "',fname])
end

% Obtain Gravity, Scale and Water density factors from
wamit_5S.out file
n=0;
ii = 1;
found = 0;
while ii<length(data) && found == 0
    k = strfind(data(ii), 'Gravity:');
    if ~isempty(k{1})
        n = ii;
        found = 1;
        C = textscan(data{n},'%s %f %s %s %f');
        gravity = C{2}; scale=C{5};
        C = textscan(data{n+1},'%s %s %f %s %s %f ');
        rho = C{6};
    end
    ii = ii+1;
end
```

```
%Read input file WAMIT_5S.4
fid1 = fopen(InputFile);
data1=textscan(fid1, '%f %f %d %f %f %f %f',
'HeaderLines',0);
fclose(fid1);

[sig(:,1), sig(:,2), sig(:,3),sig(:,4), sig(:,5), sig(:,6),
sig(:,7)]=deal(data1{:});


    if isempty(sig)
        Flag = 0;
        disp('  ')

disp('===========================================================
=====')
        disp(['no data in file "',InputFile])
        disp('---------------------------------------------------
-------------')
        return
    end

  %  RAO manipulation (new arrangement of columns )
% Ordered by: heading and Dof
r=sortrows(sig,3); %order sig by DOF
r1=sortrows(r,2); % order r by Heading
r2=sortrows(r1,3); % order r1 by DOF



% Obtain Headings (directions) and periods from wami_S.4

 size_sig=size(sig);
 n_dir=1;
 n_period=1;
 Period(1)=sig(1,1);
 Dir(1)=sig(1,2);

    for iii=1: (size_sig(1)-1)
      if sig(iii+1,1)~=sig(iii,1)
      n_period = n_period+1;
      Period(n_period) = sig(iii+1,1);
      end
      if sig(iii+1,2)~=sig(iii,2)
      n_dir = n_dir+1;
      Dir(n_dir) = sig(iii+1,2);
      end
    end
```

```
  n_dir=n_dir/n_period;
  Dir=Dir(1:n_dir);

  % Organizing by DOF and type of result (magnitude, phase
angle, real part
  %                                        and imaginary
part)
 mag=zeros(n_period, n_dir); ang=mag; rea=mag; img=mag;
%zeros matrix

for k=1:n_dof  %1: surge, 2: sway, 3: heave 4: roll 5:
pitch, 6: yaw
RAO{k,1}={mag, ang, rea, img};
end


row=0;

   for k=1:n_dof
       nn=1+(k-1)*n_dir*n_period;  %row number
       for j=1:n_dir
           for iii=1:n_period
               row=row+1;
               mag(iii,j) = r2(row,4); %groups of magnitude
for each heading
               ang(iii,j) = r2(row,5); %groups of ph. angle
for each heading
               rea(iii,j) = r2(row,6); %groups of real val.
for each heading
               img(iii,j) = r2(row,7); %groups of imag val.
for each heading
           end
       end
       if k<=3
       %add dimension to the wamit output RAO
       RAO{k,1}={mag, ang, rea, img};
       elseif k>3
       RAO{k,1}={mag/scale, ang, rea/scale, img/scale};
       end
   end

% end of direct post processing----------------------------
-----------------------

% % ------- PLOT ------
if Plot_RAO==1
 for idof=1:6 %DOF to plot;
```

```
          %   1: surge, 2: sway, 3: heave 4: roll 5: pitch,
6: yaw

   switch idof
      case 1
          motionName='Surge';
      case 2
          motionName='Sway';
      case 3
          motionName='Heave';
      case 4
           motionName='Roll';
      case 5
          motionName='Pitch';
      case 6
          motionName='Yaw';
   end
   a = RAO(idof);
   res = a{1};
   mag= res{1};
   ang=res{2};

  figure(idof)
  hold on
 for ii=1:length(heading)
    if ii<8
        if ii<4
            if idof<4
            plot(WavePeriodd,mag(:,ii),'s-')
            ylabel('Amplitud m/m','FontSize',14);
            else
            plot(WavePeriodd,mag(:,ii)*rad2deg,'s-')
            ylabel('Amplitud deg/m','FontSize',14);
            end
        else
            if idof<4
            plot(WavePeriodd,mag(:,ii),'*-')
            ylabel('Amplitud m/m','FontSize',14);
            else
            plot(WavePeriodd,mag(:,ii)*rad2deg,'*-')
            ylabel('Amplitud deg/m','FontSize',14);
            end
        end
        else
            if idof<4
            plot(WavePeriodd,mag(:,ii),'--')
            ylabel('Amplitud m/m','FontSize',14);
            else
            plot(WavePeriodd,mag(:,ii)*rad2deg,'--')
```

```
            ylabel('Amplitud deg/m','FontSize',14);
            end
        end
     end
      grid on;
      axis([min(WavePeriodd) max(WavePeriodd) -inf inf])
      set(gca, 'FontSize', 12);
      legend('Dir 0', 'Dir 30', 'Dir 60', 'Dir 90', 'Dir
120',...
           'Dir 150', 'Dir 180', 'Dir 210', 'Dir 240', ...
           'Dir 270', 'Dir 300', 'Dir 330');
       title(strcat('  ', motionName));
      xlabel('Wave Period, T(\omega) [s]','FontSize',14);
        if Plot_phase==1
figure(idof+6)
hold on
 for ii=1:12
    if ii<8
        if ii<4
                   if idof<4
            plot(WavePeriodd,ang(:,ii),'s-')
            else
            plot(WavePeriodd,ang(:,ii),'s-')

            end
        else
                   if idof<4
            plot(WavePeriodd,ang(:,ii),'*-')
            else
            plot(WavePeriodd,ang(:,ii),'*-')

            end
        end
    else
                 if idof<4
            plot(WavePeriodd,ang(:,ii),'--')
            else
            plot(WavePeriodd,ang(:,ii),'--')
            end
    end
 end

  grid on;
  axis([min(WavePeriodd) max(WavePeriodd) -inf inf]);
  set(gca, 'FontSize', 12);
  legend('Dir 0', 'Dir 30', 'Dir 60', 'Dir 90', 'Dir
120',...
         'Dir 150', 'Dir 180', 'Dir 210', 'Dir 240', ...
         'Dir 270', 'Dir 300', 'Dir 330');
```

```
  lgd.FontSize =12;
  title(strcat( motionName));
  xlabel('Wave Period, T(\omega) [s]','FontSize',14);
  ylabel(' Phase (deg) ','FontSize',14);
    end
 end
end


%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++%
%% +++++++++++ Calculate the RAO for the user-specified
point ++++++++++++%
%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++%

pt_x=pt_catamaran(1); pt_y=pt_catamaran(2);
pt_z=pt_catamaran(3);
mag=zeros(n_period, n_dir); ang=mag; rea=mag; img=mag;

RAO_ves=cell(3,1); % RAO of the specified point on the
vessel
for k=1:3
RAO_ves{k,1}={mag, ang, rea, img};
end

surge= RAO{1}; sway= RAO{2}; heave= RAO{3};
roll= RAO{4}; pitch= RAO{5}; yaw= RAO{6};

for k=1:6
    %surge for the specified point:
  if k==1
    rea=surge{3}+pitch{3}*pt_z-yaw{3}*pt_y;
    img=surge{4}+pitch{4}*pt_z-yaw{4}*pt_y;
    M=complex(rea,img);
    RAO_ves{k,1}={abs(M), angle(M)*rad2deg, rea, img};
  elseif k==2
    %sway for the specified point:
    rea=sway{3}-roll{3}*pt_z+yaw{3}*pt_x;
    img=sway{4}-roll{4}*pt_z+yaw{4}*pt_x;
    M=complex(rea,img);
    RAO_ves{k,1}={abs(M), angle(M)*rad2deg, rea, img};
  elseif k==3
    %heave for the specified point:
    rea=heave{3}+roll{3}*pt_y-pitch{3}*pt_x;
    img=heave{4}+roll{4}*pt_y-pitch{4}*pt_x;
    M=complex(rea,img);
    RAO_ves{k,1}={abs(M), angle(M)*rad2deg, rea, img};
```

```
  else
      %roll, pitch, yaw for the specified point:
%     RAO_ves{k,1}=RAO{k,1};
  end
end
% end of  specific point RAO -----------------------------
---------------



% % ------- PLOT ------
if Plot_RAO_specific==1
 for idof=1:3 %DOF to plot;
          %   1: surge, 2: sway, 3: heave 4: roll 5: pitch,
6: yaw

   switch idof
      case 1
          motionName='Longitudinal,(X) RAO Amplitud for
specific point';
      case 2
          motionName='Transversal,(Y) RAO  Amplitud for
specific point';
      case 3
          motionName=' Vertical, (Z)  RAO   Amplitud for
specific point';
      case 4
           motionName='Roll specific point';
      case 5
          motionName='Pitch specific point';
      case 6
          motionName='Yaw specific point';
   end
   a = RAO_ves(idof);
   res = a{1};
   mag= res{1};
   ang=res{2};

  figure(idof+12)
  hold on
 for ii=1:length(heading)
    if ii<8
        if ii<4
            if idof<4
            plot(WaveOmega,mag(:,ii),'s-')
            ylabel('Amplitud m/m','FontSize',14);
            else
            plot(WaveOmega,mag(:,ii)*rad2deg,'s-')
            ylabel('Amplitud deg/m','FontSize',14);
            end
```

```
        else
            if idof<4
            plot(WaveOmega,mag(:,ii),'*-')
            ylabel('Amplitud m/m','FontSize',14);
            else
            plot(WaveOmega,mag(:,ii)*rad2deg,'*-')
            ylabel('Amplitud deg/m','FontSize',14);
            end
        end
        else
            if idof<4
            plot(WaveOmega,mag(:,ii),'--')
            ylabel('Amplitud m/m','FontSize',14);
            else
            plot(WaveOmega,mag(:,ii)*rad2deg,'--')
            ylabel('Amplitud deg/m','FontSize',14);
            end
    end
 end
  grid on;
  axis([min(WaveOmega) max(WaveOmega) -inf inf])
  set(gca, 'FontSize', 12);
  legend('Dir 0', 'Dir 30', 'Dir 60', 'Dir 90', 'Dir
120',...
         'Dir 150', 'Dir 180', 'Dir 210', 'Dir 240', ...
         'Dir 270', 'Dir 300', 'Dir 330');
   title(strcat('  ', motionName));
  xlabel('Wave ang. frequency, \omega [s]','FontSize',14);

    if Plot_phase_specific==1
figure(idof+6+12)
hold on
 for ii=1:12
    if ii<8
        if ii<4
                   if idof<4
            plot(WaveOmega,ang(:,ii),'s-')
            else
            plot(WaveOmega,ang(:,ii),'s-')

            end
        else
                   if idof<4
            plot(WaveOmega,ang(:,ii),'*-')
            else
            plot(WaveOmega,ang(:,ii),'*-')

            end
        end
```

```
    else
                 if idof<4
            plot(WaveOmega,ang(:,ii),'--')
            else
            plot(WaveOmega,ang(:,ii),'--')
            end
    end
 end

  grid on;
  axis([min(WaveOmega) max(WaveOmega) -inf inf]);
  set(gca, 'FontSize', 12);
  legend('Dir 0', 'Dir 30', 'Dir 60', 'Dir 90', 'Dir
120',...
         'Dir 150', 'Dir 180', 'Dir 210', 'Dir 240', ...
         'Dir 270', 'Dir 300', 'Dir 330');
  lgd.FontSize =12;
  title(strcat( motionName));
  xlabel('Wave ang. frequencie, \omega [s]','FontSize',14);
  ylabel(' Phase (deg) ','FontSize',14);
    end
 end
end



%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%
%% --------------------- Wave Spectrum, PM ----------------
-----------------%
%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%




%
%
%         %%%%%%%%%%%   Wave Spectrum %%%%%%%%%%%%%
        q=[...
                     0.00006678 0.01365932  0.06217001
0.0658392   0.03375035  0.01002983  0.00198898  0.000301
0.00003864  0           0           ;
                     0          0.00214563  0.02410475
0.04828263  0.04291619  0.02150532  0.00687117  0.00158653
0.00029425  0.00004754  0.00000396  ;
                     0          0.00052679  0.01111834
0.03443135  0.04317776  0.02981863  0.01284596  0.0038871
0.00091726  0.00018324  0.00003299  ;
```

```
                     0           0.00013926  0.00489685
0.02164203  0.03558183  0.03130702  0.01687146  0.00625406
0.0017696   0.00041529  0.00008615  ;
                     0           0.00003855  0.00210711
0.01268044  0.02625996  0.02819974  0.01822694  0.00796477
0.00261144  0.00069875  0.00016278  ;
                     0           0.000011    0.0008929
0.00709268  0.01803586  0.02300779  0.01736074  0.00872224
0.00324048  0.00096927  0.00024929  ;
                     0           0           0.00037383
0.00383404  0.0117615   0.01749478  0.01512316  0.00858344
0.00355659  0.00117268  0.00032892  ;
                     0           0           0.00015309
0.00201725  0.00736877  0.01260839  0.01231398  0.00779276
0.00355888  0.00127997  0.00038796  ;
                     0           0           0.00006283
0.00103767  0.00446897  0.00870604  0.00950453  0.00663894
0.00331116  0.00128843  0.00041899  ;
                     0           0           0.00002553
0.00052342  0.00263708  0.00580216  0.00702121  0.00536972
0.00290336  0.00121432  0.00042125  ;
                     0           0           0.00001027
0.00025943  0.00151957  0.00375192  0.00499846  0.00415813
0.00242276  0.00108335  0.00039903  ;
                     0           0           0
0.00012654  0.00085736  0.00236325  0.00344697  0.00310216
0.0019381   0.00092243  0.00035933  ;
                     0           0           0
0.00006081  0.00047462  0.00145431  0.00231171  0.00224057
0.0014947   0.00075437  0.00030978  ;
                     0           0           0
0.00002694  0.00025819  0.00087642  0.00151247  0.00157273
0.00111633  0.00059555  0.00025709  ;
                     0           0           0
0.00001262  0.0001382   0.00051821  0.00096783  0.00107626
0.00081038  0.00045576  0.00020633  ;
                     0           0           0           0
0.00007286  0.00030109  0.00060699  0.0007199   0.00057355
0.00033926  0.00016074  ;
                     0           0           0           0
0.00003787  0.00017213  0.00037376  0.00047172  0.00039679
0.00024637  0.00012195  ;
                     0           0           0           0
0.00001621  0.00009693  0.0002263   0.00030337  0.00026893
0.00017498  0.00009036  ;
                     0           0           0           0
0.00000827  0.00005381  0.00013491  0.0001918   0.00017892
0.00012182  0.00006554  ;
```

```
                     0          0           0           0
0           0.00002948  0.00007927  0.00011938  0.00011705
0.0000833   0.00004665  ;
                     0          0           0           0
0           0.00001594  0.00004596  0.00007325  0.00007541
0.00005604  0.00003263  ;
                     0          0           0           0
0           0.00000651  0.00002631  0.00004436  0.00004792
0.00003716  0.00002248  ;
                     0          0           0           0
0           0           0.00001489  0.00002654  0.00003006
0.00002431  0.00001528  ;
                     0          0           0           0
0           0           0           0.0000157   0.00001864
0.00001572  0.00000681  ;
                     0          0           0           0
0           0           0           0           0.00000648
0.00000785  0.00000687  ];

%
%  for iii=1:length(Hs)
%
%                  if Plot_wave_spectrum ==1
%                   figure(99)
%                   hold on
%                   plot(w,Ss(iii,:))
%                   grid on
%                   set(gca, 'FontSize', 12);
% %                   hs(i)=0.5*i;
%                   legend('Hs  0.50','Hs 1.00','Hs
1.50','Hs 2.00',...
%                     'Hs 2.50','Hs 3.00','Hs 3.50','Hs
4.00',...
%                     'Hs 4.50','Hs 5.00','Hs 5.50','Hs
6.00',...
%                     'Hs 6.50','Hs 7.00','Hs 7.50','Hs
8.00',...
%                     'Hs 8.50','Hs 9.00','Hs 9.50','Hs
10.00','Hs 10.50',...
%                     'Hs11.00','Hs 11.50','Hs 12.00','Hs
12.50')
%                   title('Pierson Moskowitz Wave
Spectrum');
%                   xlabel('Angular Frequency \omega
[rad/s]','FontSize',14);
%                   ylabel('Spectrum Density [m^2·s]
','FontSize',14);
%                   clc
%                  end
```

```
%
%                S_ws(:,iii)=(Ss(iii,:))'; %Wave spectrum
amplitud
%  end



% omega=linspace(0.4,10,100);

[H O]=meshgrid(Hs,WaveOmega);

for mm=1:length(Tz)

for nn=1:length(Hs)
A=(Hs(nn)^2/(4*pi))*(2*pi/Tz(mm))^4;
B=(1/pi)*(2*pi/Tz(mm))^4;


for ii=1:length(WavePeriodd)

S_ws(ii,nn,mm)= (A*(WaveOmega(ii))^(-5)).*exp(-
B*WaveOmega(ii)^(-4));% (N. 11.4)

end
area(nn,mm)=trapz(WaveOmega,S_ws(:,nn,mm));
energy(nn,mm)=gravity*rho*area(nn,mm);
end

        if Plot_wave_spectrum ==1
            figure(98)
            hold on
            col=[0.3    0.5 1
                   0    0.3 1
                   0.5  1   1
                   0.5  1   0.5
                   0    0.3 0.2
                   0.3  0.5 0.2
                   0.5  1   0.2
                   1    1   0.5
                   1    1   0.2
                   1    0.5 0.2
                   1    0   0.2]; %color for the plot


P=surf(H,O,S_ws(:,:,mm),'Facecolor',col(mm,:),'LineStyle','
:');
              grid on
```

```
              set(gca, 'FontSize', 12);
             legend('Tz 2','Tz 3','Tz 4','Tz 5','Tz 6','Tz 
7',...
                    'Tz 8','Tz 9','Tz 10','Tz 11','Tz 12')

              title('Pierson Moskowitz Wave Spectrum');
              ylabel('\omega [rad/s]','FontSize',14);
              zlabel('Spectrum Density [m^2·s]
','FontSize',14);
              xlabel ('Hs [m]');
              clc
            %    P.EdgeColor = 'none';
        end

end

%%
% for ii=1:60
% for nn=1:25
% SS(ii,nn)=sum(S_ws(ii,nn,:));
% end
% end
% S_ws=SS;
% figure()
% surf(H,O,SS)

%%
%          %%%%%%%% End Wave SPectrum
%%%%%%%%%%%%%%%%%%%%%%%%


%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++%
%% ------- OUTPUT section------ short-term response in the 
freq. domain


format long
%% Displacements

% S_ws=flip(S_ws);


%  x_new=WavePeriodd;

  for ii=1:gaxis
    for j=1:length(heading)
```

```
      for iii=1:length(Tz)

      %Second moments of vel and acc. and Most probable
maximums (MPM)
            temp=RAO_ves{ii};
            S_tf=temp{1}; %Transfer function amplitude
            S_response(:,iii) =
(S_ws(:,2,iii)).*((S_tf(:,j)).^2); %motion response
spectrum,long crested sea S(w)*H(w)^2=response, (N,5.29)
%             S_response(:,iii) = (S_ws(:,iii,1)); %


            Z0=cumint3(WaveOmega, S_response(:,iii)); %3-
order trapz, cumulative with all elements
            m0=abs(Z0(end));                    %variance
or 0-th order spectral moment (N, 4.12)
            mo0(iii)=Z0(end);%
            Hssss(iii)=4.*sqrt(mo0(iii));%mlo=Hssss';
%(F,2.26 ; N,4.18)

             S_sq(:,iii)=S_response(:,iii).*(WaveOmega.^2);

            z2=cumint3(WaveOmega, S_sq(:,iii));
%integral (w^2*Syy, w)
            m2=abs(z2(end));         %2-nd order spectral
moment, (F,2.25; N, 4.11)

            S_r4(:,iii)=S_response(:,ii).*(WaveOmega.^4);

            z4=cumint3(WaveOmega, S_r4(:,ii));
%integral (w*Syy, w)
            m4=abs(z4(end));         %4-th order spectral
moment, (N, 4.11)


            Tpp=2*pi()*sqrt(m2/m4); %mean peaks period, (N,
4.15)
            Tzz=(2*pi()*sqrt(m0/m2)); %mean zero-upcrossing
period, (N, 4.16)

             eta=sqrt(1-Tpp^2/Tzz^2); %(N, 4.17)

            Nz=Tref/Tzz; %(N, 5.40 & 5.43)
            mpm(iii)=sqrt(m0*2*log(Nz));   %(N, 5.44,
6.114)
%             disp(strcat('Tz=', num2str(Tz),'  Nz=',
num2str(Nz)));
```

```
            mq(iii)=sqrt(m0*2*log(Nz/q(2,iii)));   %(N,
5.44, 6.114)
      end
           S_r=S_response;
            if ii==1
           S_resp{j}=S_r;
           MPM(j,:)=mpm;
           MQ(j,:)=mq;
            elseif ii==2
           S_resp{j+12}= S_r;
           MPM(12+j,:)=mpm;
           MQ(12+j,:)=mq;
            elseif ii==3
             S_resp{j+24}= S_r;
             MPM(24+j,:)=mpm;
             MQ(24+j,:)=mq;
%              elseif ii==4
%                S_resp{j+36}= S_r;
%                MPM(36+j,:)=mpm*rad2deg;
%              elseif ii==5
%                S_resp{j+48}= S_r;
%                MPM(48+j,:)=mpm*rad2deg;
%              elseif ii==6
%               S_resp{j+60}= S_r;
%               MPM(60+j,:)=mpm*rad2deg;
            end
    end

  end

%  %% Velocity
%
  for ii=1:gaxis
    for j=1:length(heading)
      for iii=1:length(Tz)
%
      %Second moments of vel and acc. and Most probable
maximums (MPM)
            temp=RAO_ves{ii};
            S_tf=temp{1}; %Transfer function amplitude
            S_response(:,iii) =
(S_ws(:,2,iii)).*WaveOmega.*((S_tf(:,j)).^2); %motion
response spectrum,long crested sea S(w)*H(w)^2=response,
(N,5.29)



            Z0=cumint3(WaveOmega, S_response(:,iii)); %3-
order trapz, cumulative with all elements
```

```
            m0=abs(Z0(end));                     %variance
or 0-th order spectral moment (N, 4.12)

            S_r4(:,iii)=S_response(:,ii).*(WaveOmega.^4);
            z4=cumint3(WaveOmega, S_r4(:,ii));
%integral (w*Syy, w)
            m4=abs(z4(end));         %4-th order spectral
moment, (N, 4.11)


            S_sq(:,iii)=S_response(:,iii).*(WaveOmega.^2);
            z2=cumint3(WaveOmega, S_sq(:,iii));
%integral (w^2*Syy, w)
            m2=abs(z2(end));         %2-nd order spectral
moment, (N, 4.11)

            Tpp=2*pi()*sqrt(m2/m4); %mean peaks period, (N,
4.16)
            Tzz=2*pi()*sqrt(m0/m2); %mean zero-upcrossing
period, (N, 4.16)

             eta=sqrt(1-Tpp^2/Tzz^2);

            Nz=Tref/Tzz;
            mpm_v(iii)=sqrt(m0*2*log(Nz));   %(N, 5.44,
6.114)
%             disp(strcat('Tz=', num2str(Tz),'  Nz=',
num2str(Nz)));

      end
           S_v=S_response;
            if ii==1
           S_resp_v{j}= S_v;
           MPM_v(j,:)=mpm_v;
            elseif ii==2
           S_resp_v{j+12}= S_v;
           MPM_v(12+j,:)=mpm_v;
            elseif ii==3
             S_resp_v{j+24}= S_v;
             MPM_v(24+j,:)=mpm_v;
%             elseif ii==4
%               S_resp_v{j+36}= S_v;
%               MPM_v(36+j,:)=mpm_v*rad2deg;
%             elseif ii==5
%               S_resp_v{j+48}= S_v;
%               MPM_v(48+j,:)=mpm_v*rad2deg;
%             elseif ii==6
%              S_resp_v{j+60}= S_v;
```

```
%               MPM_v(60+j,:)=mpm_v*rad2deg;
            end
    end

  end
%
%   %% Acelerations
%
  for ii=1:gaxis
    for j=1:length(heading)
      for iii=1:length(Tz)
%
      %Second moments of vel and acc. and Most probable
maximums (MPM)
            temp=RAO_ves{ii};
            S_tf=temp{1}; %Transfer function amplitude
            S_response(:,iii) =
(S_ws(:,2,iii)).*WaveOmega.^2.*((S_tf(:,j)).^2); %motion
response spectrum,long crested sea S(w)*H(w)^2=response,
(N,5.29)



            Z0=cumint3(WaveOmega, S_response(:,iii)); %3-
order trapz, cumulative with all elements
            m0=abs(Z0(end));                     %variance
or 0-th order spectral moment (N, 4.12)

            S_sq(:,iii)=S_response(:,iii).*(WaveOmega.^2);
            z2=cumint3(WaveOmega, S_sq(:,iii));
%integral (w^2*Syy, w)
            m2=abs(z2(end));         %2-nd order spectral
moment, (N, 4.11)

            S_r4(:,iii)=S_response(:,ii).*(WaveOmega.^4);
            z4=cumint3(WaveOmega, S_r4(:,ii));
%integral (w*Syy, w)
            m4=abs(z4(end));         %4-th order spectral
moment, (N, 4.11)

            Tpp=2*pi()*sqrt(m2/m4); %mean peaks period, (N,
4.16)
            Tzz=2*pi()*sqrt(m0/m2); %mean zero-upcrossing
period, (N, 4.16)

             eta=sqrt(1-Tpp^2/Tzz^2);

            Nz=Tref/Tzz;
```

```
            mpm_a(iii)=sqrt(m0*2*log(Nz));   %(N, 5.44,
6.114)
%             disp(strcat('Tz=', num2str(Tz),'  Nz=',
num2str(Nz)));

      end
           S_a=S_response;
            if ii==1
           S_resp_a{j}=S_a;
           MPM_a(j,:)=mpm_a;
            elseif ii==2
           S_resp_a{j+12}= S_a;
           MPM_a(12+j,:)=mpm_a;
            elseif ii==3
             S_resp_a{j+24}= S_a;
             MPM_a(24+j,:)=mpm_a;
%             elseif ii==4
%               S_resp_a{j+36}= S_a;
%               MPM_a(36+j,:)=mpm_a*rad2deg;
%             elseif ii==5
%               S_resp_a{j+48}= S_a;
%               MPM_a(48+j,:)=mpm_a*rad2deg;
%             elseif ii==6
%              S_resp_a{j+60}= S_a;
%              MPM_a(60+j,:)=mpm_a*rad2deg;
            end
    end

  end
  MPM(isnan(MPM))     = [0];
  MPM_v(isnan(MPM_v)) = [0];
  MPM_a(isnan(MPM_a)) = [0];

   MQ(isnan(MQ))     = [0];
   MQ(isinf(MQ))     = [0];

%%%%%%%%%%FINAL PLOT%%%%%%%%%%%%%%
  if Plot_S_Response==1
%%%%%%%%%%%%%
%%%%%%%%%%%%%
% for  Direction=0:30:180
 Direction=90; % Select between 0:30:330
 Hss=1;    % Select between 0.5:0.5:12.5
 T0z=5;    % Select between 2:12
 gaxis_esp=2; % Select X=1, Y=2 or Z=3
 %%%%%%%%%%
 %%%%%%%%%%
```

```
  figure(100)
    subplot(3,1,1)
  hold on
 switch gaxis_esp
      case 1
          motionName='X';
      case 2
          motionName='Y';
      case 3
          motionName='Z';
   end
     a = RAO_ves(gaxis_esp);
   res = a{1};
   mag= res{1}; %ang=res{2};

%
% %    f0_S = linespace(max(mag(:,Direction/30+1)));
% % Tf_Vacc150_S= pchip(f0,Tf_Vacc150,f0_S);
% figure()
% x = -3:3;
%        y = [-1 -1 -1 0 1 1 1];
%        t = omega;
%
plot(x_new,(mag(:,Direction/30+1)),'o',omega,pchip(x_new,(m
ag(:,Direction/30+1)),omega))
plot(WaveOmega,mag(:,Direction/30+1),'LineWidth',2)
%
% %    plot(x_new,flip(mag(:,Direction/30+1)),'s-
','LineWidth',2)
   grid on;
% %   axis([min(w) max(w) -inf inf])
   set(gca, 'FontSize', 12);
   legend(['Specific position:
X=',num2str(pt_catamaran(1)),'
Y=',num2str(pt_catamaran(2)),'
Z=',num2str(pt_catamaran(3))])
    title(['Vessel transfer function RAO:
',num2str(motionName),';Direction ',num2str(Direction)]);%
    xlabel('Angular Frequency \omega
[rad/s]','FontSize',14);
%    if DegOF<4
    ylabel('Amplitud m/m','FontSize',14);
%    else
%    ylabel('Amplitud deg/m','FontSize',14);
%    end
%



  subplot(3,1,2)
```

```
hold on
S_wss=S_ws(:,Hss*2,T0z-1);
plot(WaveOmega,S_wss,'LineWidth',2)

%   plot(w,Ss(Hss*2,:),'-','LineWidth',2)
  grid on
  set(gca, 'FontSize', 12);
  legend(['Hs ',num2str(Hss),'; Tz ',num2str(T0z)])
  title('Pierson Moskowitz Wave Spectrum');
  xlabel('Angular Frequency \omega [rad/s]','FontSize',14);
  ylabel(' Spectral Dens.[m^2·s]    ','FontSize',14);
  areas=trapz(WavePeriodd',S_wss);

  subplot(3,1,3)
  hold on
  d=gaxis_esp*12-12+(Direction/30+1);
   a = S_resp(d);
   aa=a{1};
   resa=aa(:,T0z-1);

   b = S_resp_v(d);
   bb=b{1};
   resb=bb(:,T0z-1);

   c = S_resp_a(d);
   cc=c{1};
   resc=cc(:,T0z-1);
%info for this particular response
            Z_0=cumint3(WaveOmega, resa); %3-order trapz,
cumulative with all elements
            m_0=abs(Z_0(end));      %variance or 0-th order
spectral moment (N, 4.12)
            std_dv=sqrt(m_0); %stand deviation
            Hs_ss=4.*sqrt(m_0); %(F,2.26 ; N,4.18)
                        S_squ(:,1)=resa.*(WaveOmega.^2);
            z_2=cumint3(WaveOmega, S_squ);
%integral (w^2*Syy, w)
            m_2=abs(z_2(end));         %2-nd order spectral
moment, (F,2.25; N, 4.11)

            S_r_4(:,1)=resa.*(WaveOmega.^4);
            z_4=cumint3(WaveOmega, S_r_4);
%integral (w*Syy, w)
            m_4=abs(z_4(end));         %4-th order spectral
moment, (N, 4.11)
```

```
            Tpp_sp=2*pi()*sqrt(m_2/m_4); %mean peaks
period, (N, 4.15)
            Tzz_sp=(2*pi()*sqrt(m_0/m_2)); %mean zero-
upcrossing period, (N, 4.16)
            eta_sp=sqrt(1-Tpp_sp^2/Tzz_sp^2); %(N, 4.17)
            et_2=sqrt(1-((m_2)^2/(m_0*m_4)));

            Nz_sp=Tref/Tzz_sp; %(N, 5.40 & 5.43)
            mppm=sqrt(m_0*2*log(sqrt(1-eta_sp^2)*Nz_sp));%
            mqq=sqrt(m_0*2*log(Nz/q(2,T0z-1)));
%%%%%%%%

%   if DegOF<4
       plot(WaveOmega,resa,'-','LineWidth',2)
       plot(WaveOmega,resb,'--','LineWidth',2)
       plot(WaveOmega,resc,':','LineWidth',2)
   legend('Displacement, [m^2*s]','Velocity, [m^2*s^2]',
'Aceleration, [m^2*s^3]')
%   else
%       plot(w,resa(:,Hss)*rad2deg,'--','LineWidth',50)
%       plot(w,resb(:,Hss)*rad2deg)
%       plot(w,resc(:,Hss)*rad2deg)
%   legend('Displacement, [deg^2*s]','Velocity,
[deg^2*s^2]', 'Aceleration, [deg^2*s^3]')
%   end
     grid on;
%   axis([min(w) max(w) -inf inf])
   set(gca, 'FontSize', 12);
%
    title('Vessel response motion');
   xlabel('Angular Frequency \omega
[rad/s]','FontSize',14);
   ylabel('Spectrum Dens.[m^2·s] ','FontSize',14);
%
%    format short


   MPM_Resp=MPM(d,T0z-1)
   MPM_velocities=MPM_v(d,T0z-1)
   MPM_accelerations=MPM_a(d,T0z-1)
  end
%   end
%% Short Term response
Heading_esp=30;
gaxis_es=2; % Select X=1, Y=2 or Z=3
figure(74)
plot([min(Tz):max(Tz)]',MPM(12*gaxis_es-
12+((Heading_esp/30)+1),:)) %double amplitud
grid on
 switch gaxis_es
```

```
        case 1
            motionName='X';
        case 2
            motionName='Y';
        case 3
            motionName='Z';
     end
title('Short Term Response, Displacement for Y')
    xlabel('Tz[s]','FontSize',14);
    ylabel('Amplitud m/m (unit per Hs)','FontSize',14);
    legend('\beta =30°, ')
%%
% [PKS,LOCS] = findpeaks(Sest7.S,Sest.w);
% display(LOCS(2),'The two-nodded natural at freq')
% display(LOCS(3),'The three-nodded natural at freq')
% figure
% hold on
% findpeaks(log(Sest7.S),Sest.w)
% findpeaks(Sest7.S,Sest.w)
format short
%%

%max displacements
Max_X=max(max(MPM(1:12,:)))
Max_Y=max(max(MPM(13:24,:)))
Max_Z=max(max(MPM(25:36,:)))
%max velocity
MaxV_X=max(max(MPM_v(1:12,:)))
MaxV_Y=max(max(MPM_v(13:24,:)))
MaxV_Z=max(max(MPM_v(25:36,:)))
%max acelerations
MaxA_X=max(max(MPM_a(1:12,:)))
MaxA_Y=max(max(MPM_a(13:24,:)))
MaxA_Z=max(max(MPM_a(25:36,:)))

if PlotMPM==1
 for kkk=1:3
 for kk=1:3
        switch kk
        case 1
            motionName='X';
        case 2
            motionName='Y';
        case 3
            motionName='Z';
     end
%     figure(80)
%     hold on
% plot([2:12],MPM(d,:))
```

```
% figure(81)
% hold on
% plot([2:12],MPM(d+12,:))
% figure(82)
% hold on
% plot([2:12],MPM(d+24,:))
% end


%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++

% x=[70.0   68.0    66.0    64.0    62.0    60.0    58.0
56.0    54.0    52.0    50.0    48.0    40.0    32.0
24.0    16.0    8.0 0.0 -8.0    -16.0   -24.0   -32.0   -
40.0   -45.0   -50.0   -58.0   -63.0   -67.0   -70.2];
%
% y=[30.00  29.95   29.90   29.85   29.80   29.70   29.40
29.00   28.00   27.00   26.00   25.00   23.50   22.20
21.10   20.40   20.20   20.15   20.10   20.00   19.90
19.50   18.20   10.00   0.00];
%   [XX,YY]=meshgrid(x,y);
% ZZ=[...
% 15.00 15.00   15.00   15.00   15.00   15.00   15.00
15.00   15.00   15.00   15.00   15.00   15.00   15.00
15.00   15.00   15.00   15.00   15.00   15.00   15.00
15.00   15.00   15.00   15.00   15.00   15.00   15.00
15.00
% 15.00 14.01   12.95   11.90   11.62   11.34   11.06
10.78   10.50   10.23   9.96    9.69    9.42    9.15
8.88    8.61    8.20    8.15    8.21    8.27    8.33
8.39    8.45    8.51    8.57    8.63    8.69    8.75
8.81
% 15.00 14.01   12.80   11.60   10.98   10.36   9.74
9.12    8.50    8.31    8.12    7.93    7.74    7.55
7.36    7.17    6.80    6.87    6.94    7.01    7.08
7.15    7.22    7.29    7.36    7.43    7.50    7.57
7.64
% 15.00 14.01   12.73   11.45   10.24   9.03    7.82
6.61    5.41    5.25    5.09    4.93    4.77    4.61
4.45    4.29    3.97    4.15    4.33    4.51    4.69
4.87    5.05    5.23    5.41    5.59    5.77    5.95
6.13
% 15.00 14.01   12.69   11.38   9.76    8.14    6.90
4.90    3.28    3.06    2.84    2.62    2.40    2.18
1.96    1.74    1.27    1.35    1.43    1.51    1.59
1.67    1.75    1.83    1.91    1.99    2.09    2.17
2.25
```

% 15.00 14.01 12.58 11.00 9.00 7.22 5.70
3.83 2.00 1.83 1.66 1.49 1.32 1.15
0.98 0.81 0.49 0.57 0.65 0.73 0.81
0.89 0.97 1.05 1.13 1.21 1.29 1.37
1.45
% 15.00 14.01 12.45 10.50 8.40 6.55 4.70
3.10 1.50 1.36 1.22 1.06 0.90 0.74
0.58 0.42 0.24 0.33 0.39 0.45 0.51
0.57 0.63 0.69 0.75 0.81 0.87 0.93
0.98
% 15.00 14.01 12.35 10.00 7.90 5.95 4.00
2.60 1.20 1.08 0.96 0.83 0.70 0.57
0.44 0.31 0.18 0.15 0.19 0.23 0.27
0.31 0.35 0.39 0.43 0.47 0.51 0.55
0.59
% 15.00 14.01 11.50 9.00 7.00 5.10 3.20
2.00 0.95 0.88 0.78 0.67 0.56 0.45
0.34 0.23 0.11 0.03 0.04 0.05 0.08
0.11 0.14 0.17 0.20 0.23 0.26 0.28
0.30
% 15.00 14.01 9.70 6.00 3.80 2.65 1.50
1.00 0.78 0.57 0.50 0.42 0.38 0.27
0.18 0.10 0.02 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01
% 15.00 14.00 9.30 5.50 3.40 2.40 1.30
0.80 0.65 0.46 0.39 0.31 0.27 0.15
0.07 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00
% 15.00 14.01 9.70 6.00 3.80 2.65 1.50
1.00 0.78 0.57 0.50 0.42 0.38 0.27
0.18 0.10 0.02 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01
% 15.00 14.01 11.50 9.00 7.00 5.10 3.20
2.00 0.95 0.88 0.78 0.67 0.56 0.45
0.34 0.23 0.11 0.03 0.04 0.05 0.08
0.11 0.14 0.17 0.20 0.23 0.26 0.28
0.30
% 15.00 14.01 12.35 10.00 7.90 5.95 4.00
2.60 1.20 1.08 0.96 0.83 0.70 0.57
0.44 0.31 0.18 0.15 0.19 0.23 0.27
0.31 0.35 0.39 0.43 0.47 0.51 0.55
0.59
% 15.00 14.01 12.45 10.50 8.40 6.55 4.70
3.10 1.50 1.36 1.22 1.06 0.90 0.74
0.58 0.42 0.24 0.33 0.39 0.45 0.51

0.57 0.63 0.69 0.75 0.81 0.87 0.93
0.98
% 15.00 14.01 12.58 11.00 9.00 7.22 5.70
3.83 2.00 1.83 1.66 1.49 1.32 1.15
0.98 0.81 0.49 0.57 0.65 0.73 0.81
0.89 0.97 1.05 1.13 1.21 1.29 1.37
1.45
% 15.00 14.01 12.69 11.38 9.76 8.14 6.90
4.90 3.28 3.06 2.84 2.62 2.40 2.18
1.96 1.74 1.27 1.35 1.43 1.51 1.59
1.67 1.75 1.83 1.91 1.99 2.09 2.17
2.25
% 15.00 14.01 12.73 11.45 10.24 9.03 7.82
6.61 5.41 5.25 5.09 4.93 4.77 4.61
4.45 4.29 3.97 4.15 4.33 4.51 4.69
4.87 5.05 5.23 5.41 5.59 5.77 5.95
6.13
% 15.00 14.01 12.80 11.60 10.98 10.36 9.74
9.12 8.50 8.31 8.12 7.93 7.74 7.55
7.36 7.17 6.80 6.87 6.94 7.01 7.08
7.15 7.22 7.29 7.36 7.43 7.50 7.57
7.64
% 15.00 14.01 12.95 11.90 11.62 11.34 11.06
10.78 10.50 10.23 9.96 9.69 9.42 9.15
8.88 8.61 8.09 8.15 8.21 8.27 8.33
8.39 8.45 8.51 8.57 8.63 8.69 8.75
8.81
% 15.00 14.01 13.18 12.35 12.24 12.13 12.02
11.91 11.75 11.55 11.30 11.05 10.80 10.55
10.30 10.05 9.57 9.62 9.67 9.72 9.76
9.80 9.84 9.88 9.92 9.96 10.01 10.06
10.11
% 15.00 14.01 13.45 12.90 12.73 12.56 12.39
12.22 12.05 11.90 11.75 11.60 11.45 11.30
11.15 11.00 10.74 10.78 10.81 10.84 10.86
10.89 10.91 10.94 10.96 10.99 11.01 11.04
11.06
% 15.00 14.01 13.65 13.30 13.06 12.82 12.58
12.34 12.10 12.02 11.94 11.86 11.78 11.70
11.62 11.54 11.39 11.41 11.43 11.45 11.47
11.49 11.51 11.53 11.55 11.57 11.59 11.61
11.63
% 15.00 14.01 13.74 13.48 13.21 12.94 12.67
12.40 12.15 12.09 12.03 11.97 11.91 11.85
11.79 11.71 11.58 11.60 11.62 11.64 11.66
11.68 11.70 11.72 11.74 11.76 11.78 11.78
11.78
% 15.00 14.01 13.83 13.66 13.37 13.08 12.79
12.50 12.20 12.13 12.06 11.99 11.92 11.85

```
11.79   11.71   11.60   11.62   11.64   11.66   11.68
11.70   11.72   11.74   11.76   11.78   11.80   11.80
11.80];
%
% figure(1)
% hold on
% n=5;
%
% Vep=surf(XX/n,YY/n,(ZZ-8)/n,'Facecolor',([0.3,0.5,0.5]))
% Ves=surf(XX/n,-YY/n,(ZZ-8)/n,'Facecolor',([0.3,0.5,0.5]))
% alpha 1
% Vep.EdgeColor = ([0.3,0.5,0.7])
% Ves.EdgeColor = ([0.3,0.5,0.7])
%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++


% The peaks function on a polar grid
tz=2:1:12;
B=0:30:330;


% bp(1,1:length(B))=B;bp(1,length(B)+1)=B(1);
bp=B./(180/pi);

[t,H] = meshgrid(tz,bp);
% P=zeros(length(B)+1,length(tz));
% P(1:length(B),:) =rand(length(B),length(tz));
% P(length(B)+1,:)=P(1,:);
figure(105)
hold on
    %0deg
330deg
    if kkk==1
        subplot(3,3,1+kk-1+kkk-1)
   P= (MPM((1+kk*12-12:12+kk*12-12),:))';
%    figure(kk+104);
   uu=[Max_X,Max_Y,Max_Z];
   title(['Max MPM,
',num2str(motionName),'=',num2str(uu(kk))])
   hold on
    elseif kkk==2
        subplot(3,3,3+kk-1+kkk-1)
   P= (MPM_v((1+kk*12-12:12+kk*12-12),:))';
%    figure(kk+108);
   uv=[MaxV_X,MaxV_Y,MaxV_Z];
   title(['Max MPM_v,
',num2str(motionName),'=',num2str(uv(kk))])
```

```
   hold on
    else
        subplot(3,3,5+kk-1+kkk-1)
  P= (MPM_a((1+kk*12-12:12+kk*12-12),:))';
%   figure(kk+112);
  vv=[MaxA_X,MaxA_Y,MaxA_Z];
  title(['Max MPM_a,
',num2str(motionName),'=',num2str(vv(kk))])
  hold on
    end
% P =[ 1     0     0     0     0     0     0.11     0     0
0     0     0 %Tz=min
%      1     0     0     0     0     0     0.10     0     0
0     0     0
%      1     0     0     0     0     0     0.09     0     0
0     0     0
%      1     0     0     0     0     0     0.08     0     0
0     0     0
%      1     0     0     0     0     0     0.07     0     0
0     0     0
%      1     0     0     0     0     0     0.06     0     0
0     0     0
%      1     0     0     0     0     0     0.05     0     0
0     0     0
%      1     0     0     0     0     0     0.04     0     0
0     0     0
%      1     0     0     0     0     0     0.03     0     0
0     0     0
%      1     0     0     0     0     0     0.02     0     0
0     0     0
%      1     0     0     0     0     0     0.01     0     0
0     0     0];%Tz=max
t2 = [0 330]*pi/180;
r2 = [tz(1) tz(end)];
% Axis property cell array
axprop = {'DataAspectRatio',[1 1 0.5],...
          'Xlim', [-tz(end)-3 tz(end)+3],       'Ylim', [-
tz(end)-3 tz(end)+3]};%,...
%            'XTick',[-4 -2 0 2 4],    'YTick',[-4 -2 0 2
4]};'View', [-20 38],


zlabel('MPM')
polarplot3d(P,'plottype','surf','angularrange',t2,'radialra
nge',r2,...
              'tickspacing',15,...

'plotprops',{'Linestyle','none'},'polargrid',{0
1.5/pi});%'colordata',gradient(P),
```

```
set(gca,axprop{:});
xlabel('Period [s]')
ylabel('Period [s]')

% alpha 0.4
 end
 if kkk==3
     figure(106)

polarplot3d(P,'plottype','surf','angularrange',t2,'radialra
nge',r2,...
              'tickspacing',15,...

'plotprops',{'Linestyle','none'},'polargrid',{0 1.5/pi});
          xlabel('Period [s]')
ylabel('Period [s]')
set(gca,axprop{:});
title(['Max MPM_a,
',num2str(motionName),'=',num2str(MaxA_Z)])
MaxA_Z=max(max(MPM_a(25:36,:)));
legend(['Max=',num2str(MaxA_Z)])
 end
 end
end

%% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++



% figure(105)
% subplot(3,3,1)
% legend(['Max=',num2str(Max_X)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,2)
% legend(['Max=',num2str(Max_Y)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,3)
% legend(['Max=',num2str(Max_Z)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,4)
%
legend(['Max=',num2str(MaxV_X)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,5)
%
legend(['Max=',num2str(MaxV_Y)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,6)
```

```
%
legend(['Max=',num2str(MaxV_Z)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,7)
%
legend(['Max=',num2str(MaxA_X)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,8)
%
legend(['Max=',num2str(MaxA_Y)],'Location','NorthOutside')
% legend BOXOFf
% subplot(3,3,9)
%
legend(['Max=',num2str(MaxA_Z)],'Location','NorthOutside')
% legend BOXOFf



% end
 disp('------ Run Ends Nice ------');
```

A.2 Code 2-Cartilla

```
%----------------------------
% Cleaning & format comands
clear
close all
clc
format compact
format short
%----------------------------

x=[70.0 68.0    66.0    64.0    62.0    60.0    58.0
56.0    54.0    52.0    50.0    48.0    40.0    32.0
24.0    16.0    8.0 0.0 -8.0    -16.0   -24.0   -32.0   -
40.0   -45.0   -50.0   -58.0   -63.0   -67.0   -70.2];

y=[30.00    29.95   29.90   29.85   29.80   29.70   29.40
29.00   28.00   27.00   26.00   25.00   23.50   22.20
21.10   20.40   20.20   20.15   20.10   20.00   19.90
19.50   18.20   10.00   0.00];

z=[...
99.00   99.00   99.00   99.00   99.00   99.00   99.00
99.00   99.00   99.00   18.00   18.00   18.00   18.00
18.00   18.00   18.00   18.00   18.00   18.00   18.00
18.00   18.00   18.00   18.00   18.00   18.00   18.00
18.00   ;
99.00   99.00   99.00   99.00   99.00   99.00   99.00
99.00   99.00   18.00   10.62   10.10   10.00   10.00
10.00   10.00   10.00   10.00   10.00   10.00   10.00
10.00   10.00   10.00   10.00   10.00   10.00   10.00
10.00   ;
99.00   99.00   99.00   99.00   99.00   99.00   99.00
99.00   18.00   10.69   9.61    9.34    9.00    9.00
9.00    9.00    9.00    9.00    9.00    9.00    9.00
9.00    9.00    9.00    9.00    9.00    9.00    9.00
9.00    ;
99.00   99.00   99.00   99.00   99.00   99.00   99.00
18.00   11.90   9.37    8.79    8.39    8.00    8.00
8.00    8.00    8.00    8.00    8.00    8.00    8.00
8.00    8.00    8.00    8.00    8.00    8.00    8.00
8.00    ;
99.00   99.00   99.00   99.00   99.00   99.00   18.00
12.02   9.54    7.64    6.97    6.47    6.00    6.00
6.00    6.00    6.00    6.00    6.00    6.00    6.00
6.00    6.00    6.00    6.00    6.00    7.00    8.00
8.00    ;
99.00   99.00   99.00   99.00   99.00   18.00   11.54
8.87    6.82    5.09    4.23    3.60    3.00    3.00
3.00    3.00    3.00    3.00    3.00    3.00    3.00
```

3.00	3.00	3.00	3.00	4.00	7.00	8.00
8.00	;					
99.00	99.00	99.00	99.00	18.00	11.45	8.74
6.66	4.90	3.35	2.40	1.69	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	2.00	7.00	8.00
8.00	;					
99.00	99.00	99.00	18.00	11.68	9.06	7.05
5.36	3.87	2.52	1.58	0.82	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	1.10	7.00	8.00
8.00	;					
99.00	99.00	18.00	12.08	9.63	7.75	6.16
4.76	3.50	2.34	1.49	0.73	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	7.00	8.00
8.00	;					
99.00	18.00	13.44	10.14	8.37	6.88	5.57
4.38	3.29	2.27	1.51	0.74	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	7.00	8.00
8.00	;					
18.00	13.11	10.89	9.09	7.61	6.35	5.23
4.20	3.26	2.32	1.51	0.74	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	7.00	8.00
8.00	;					
17.30	12.31	10.24	8.65	7.31	6.13	5.07
4.09	3.17	2.32	1.51	0.74	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	7.00	8.00
8.00	;					
17.10	12.16	10.12	8.55	7.23	6.06	5.01
4.04	3.14	2.29	1.49	0.73	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	7.00	8.00
8.00	;					
17.10	12.19	10.16	8.60	7.29	6.13	5.08
4.12	3.22	2.38	1.58	0.82	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	1.10	7.00	8.00
8.00	;					
17.10	12.45	10.53	9.05	7.80	6.71	5.72
4.80	3.95	3.16	2.40	1.69	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	2.00	7.00	8.00
8.00	;					
17.10	13.03	11.34	10.05	8.96	8.00	7.13
6.33	5.59	4.89	4.23	3.60	3.00	3.00

```
3.00    3.00    3.00    3.00    3.00    3.00    3.00
3.00    3.00    3.00    3.00    4.00    7.00    8.00
8.00    ;
17.10   13.90   12.57   11.55   10.69   9.93    9.25
8.62    8.04    7.49    6.97    6.47    6.00    6.00
6.00    6.00    6.00    6.00    6.00    6.00    6.00
6.00    6.00    6.00    6.00    6.00    7.00    8.00
8.00    ;
17.10   14.47   13.38   12.55   11.85   11.23   10.67
10.15   9.67    9.22    8.79    8.39    8.00    8.00
8.00    8.00    8.00    8.00    8.00    8.00    8.00
8.00    8.00    8.00    8.00    8.00    8.00    8.00
8.00    ;
17.10   14.76   13.79   13.05   12.42   11.87   11.37
10.91   10.49   10.09   9.71    9.34    9.00    9.00
9.00    9.00    9.00    9.00    9.00    9.00    9.00
9.00    9.00    9.00    9.00    9.00    9.00    9.00
9.00    ;
17.10   15.05   14.20   13.55   13.00   12.52   12.08
11.68   11.30   10.95   10.62   10.30   10.00   10.00
10.00   10.00   10.00   10.00   10.00   10.00   10.00
10.00   10.00   10.00   10.00   10.00   10.00   10.00
10.00   ;
17.10   15.34   14.61   14.05   13.58   13.16   12.79
12.44   12.12   11.82   11.53   11.26   11.00   11.00
11.00   11.00   11.00   11.00   11.00   11.00   11.00
11.00   11.00   11.00   11.00   11.00   11.00   11.00
11.00   ;
17.10   15.63   15.02   14.55   14.16   13.81   13.49
13.20   12.94   12.68   12.44   12.22   12.00   12.00
12.00   12.00   12.00   12.00   12.00   12.00   12.00
12.00   12.00   12.00   12.00   12.00   12.00   12.00
12.00   ;
17.10   15.86   15.34   14.95   14.62   14.32   14.06
13.82   13.59   13.38   13.17   12.98   12.80   12.80
12.80   12.80   12.80   12.80   12.80   12.80   12.80
12.80   12.80   12.80   12.80   12.80   12.80   12.80
12.80   ;
17.10   15.92   15.43   15.05   14.73   14.45   14.20
13.97   13.75   13.55   13.36   13.17   13.00   13.00
13.00   13.00   13.00   13.00   13.00   13.00   13.00
13.00   13.00   13.00   13.00   13.00   13.00   13.00
13.00   ;
17.10   15.92   15.43   15.05   14.73   14.45   14.20
13.97   13.75   13.55   13.36   13.17   13.00   13.00
13.00   13.00   13.00   13.00   13.00   13.00   13.00
13.00   13.00   13.00   13.00   13.00   13.00   13.00
13.00   ];
```

```
c=0;
for m=1:length(x)
    for n=1:length(y)
        if z(n,m)<50
        c=c+1;
    A(c,:)=[x(m),y(n),z(n,m)];

        end
    end
end
A % transverse

c=0;
for m=1:length(y)
    for n=1:length(x)
        if z(m,n)<50
        c=c+1;
    B(c,:)=[x(n),y(m),z(m,n)];

        end
    end
end
B % logitudinal
```

A.3 Code 3 - Wave Spectrum PM

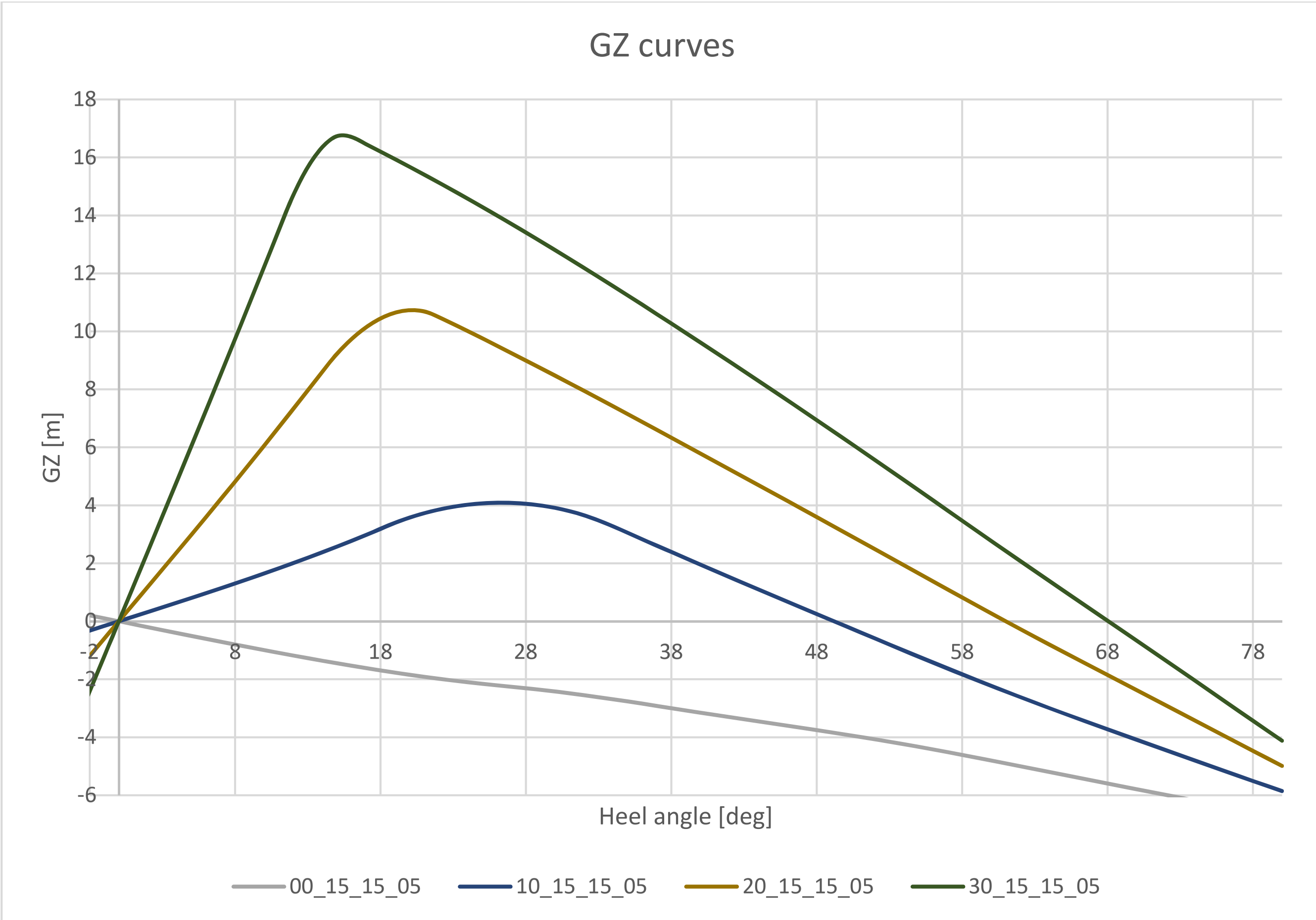
```
clc
clear all, close all

Tz=2:12;
Hs=0.5:0.5:12.5;
% omega=0:0.1:4;
omega=[...
0.1
0.2
0.3
0.4
0.48
0.52
0.55
0.57
0.6
0.63
0.66
0.68
0.7
0.74
0.9
0.97
1
1.05
1.14
1.18
1.26
1.3
1.37
1.4
1.53
1.57
1.6
1.67
1.81
1.9
1.93
2
2.2
2.5
2.7
3
3.2
3.5
3.7
4];
% omega=linspace(0.1,10,500);
[H O]=meshgrid(Hs,omega);
```

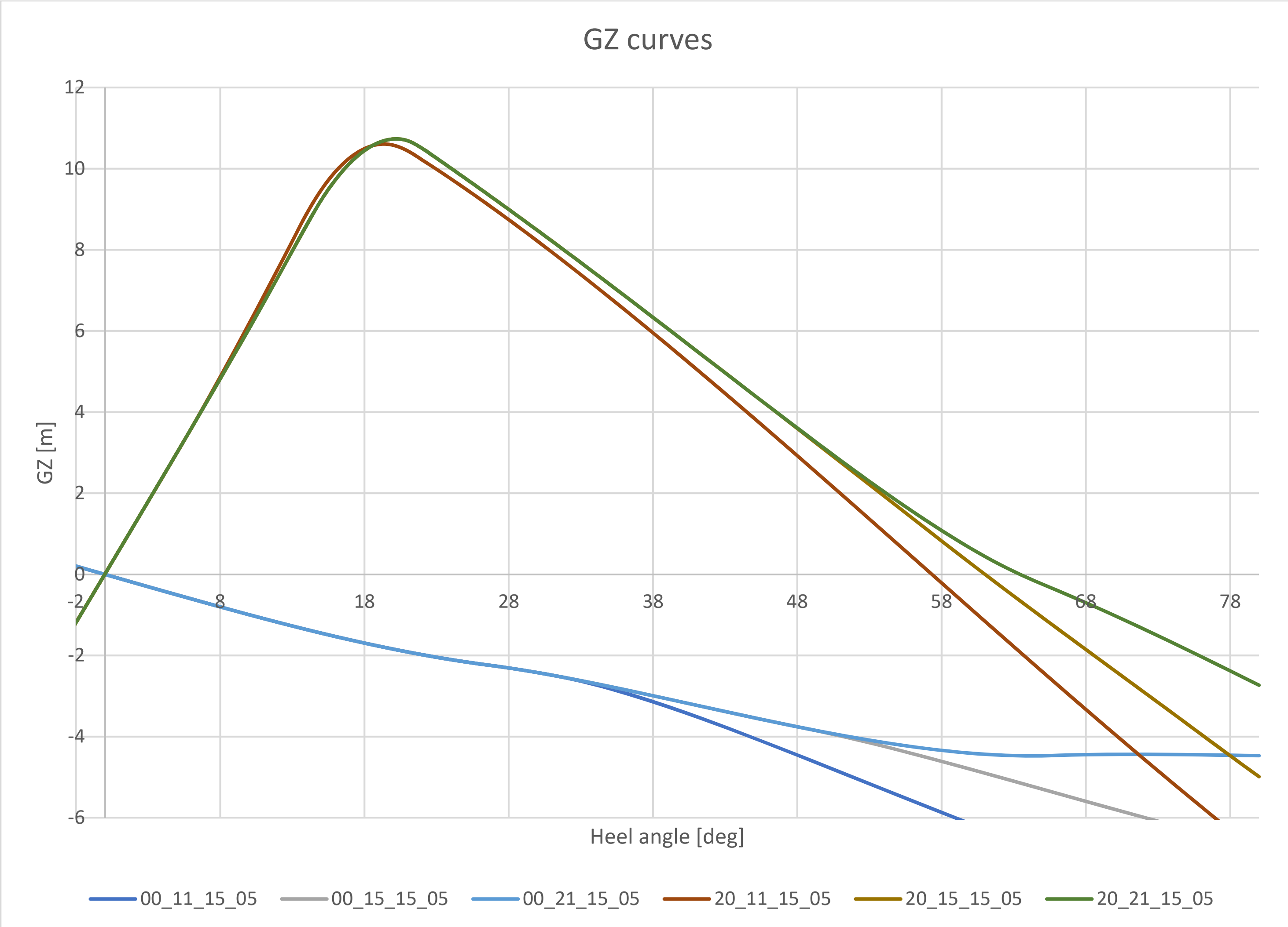
```
for mm=1:length(Tz)

for nn=1:length(Hs)
A=(Hs(nn)^2/(4*pi))*(2*pi/Tz(mm))^4;
B=(1/pi)*(2*pi/Tz(mm))^4;

for ii=1:length(omega)

S(ii,nn,mm)= (A*(omega(ii))^(-5)).*exp(-B*omega(ii)^(-4));%
(N. 11.4)

end
area(nn,mm)=trapz(omega,S(:,nn,mm));
energy(nn,mm)=9.81*1025*area(nn,mm);
end
figure(1)
hold on
col=[0.3    0.5 1
       0    0.3 1
       0.5  1   1
       0.5  1   0.5
       0    0.3 .2
       0.3  0.5 .2
       0.5  1   .2
       1    1   0.5
       1    1   .2
       1    0.5 .2
       1    0   .2];

P=surf(H,O,S(:,:,mm),'Facecolor',col(mm,:),'LineStyle',':',
'LineWidth',0.05,'EdgeColor','[0.5,0.5,0.5]')%
  grid on
  set(gca, 'FontSize', 12);
 legend('Tz 2','Tz 3','Tz 4','Tz 5','Tz 6','Tz 7',...
        'Tz 8','Tz 9','Tz 10','Tz 11','Tz 12')
    alpha 0.78
%      shadowplot x
  title('Pierson Moskowitz Wave Spectrum');
  ylabel('\omega [rad/s]','FontSize',14);
  zlabel('Spectrum Density [m^2·s] ','FontSize',14);
  xlabel ('Hs [m]');
%  ylim([0,5])
%     P.EdgeColor = 'none';

end
axprop = {'View', [60 25]};%DataAspectRatio',[1 1 1],
set(gca,axprop{:});
```

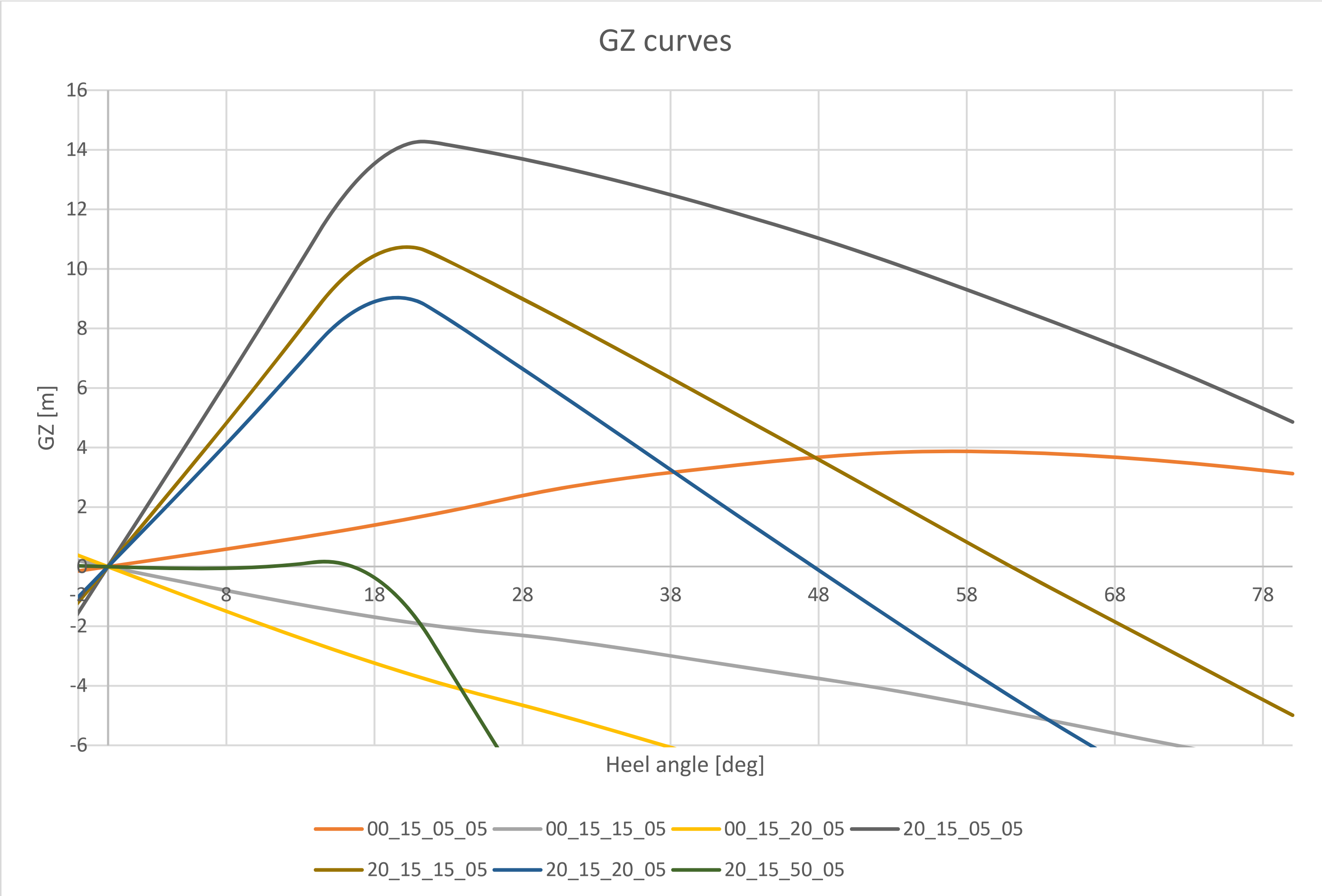
```
Hss=25;
Tzz= 1;

S_ws=S(:,Hss,Tzz);
areas=trapz(omega',S_ws);
```

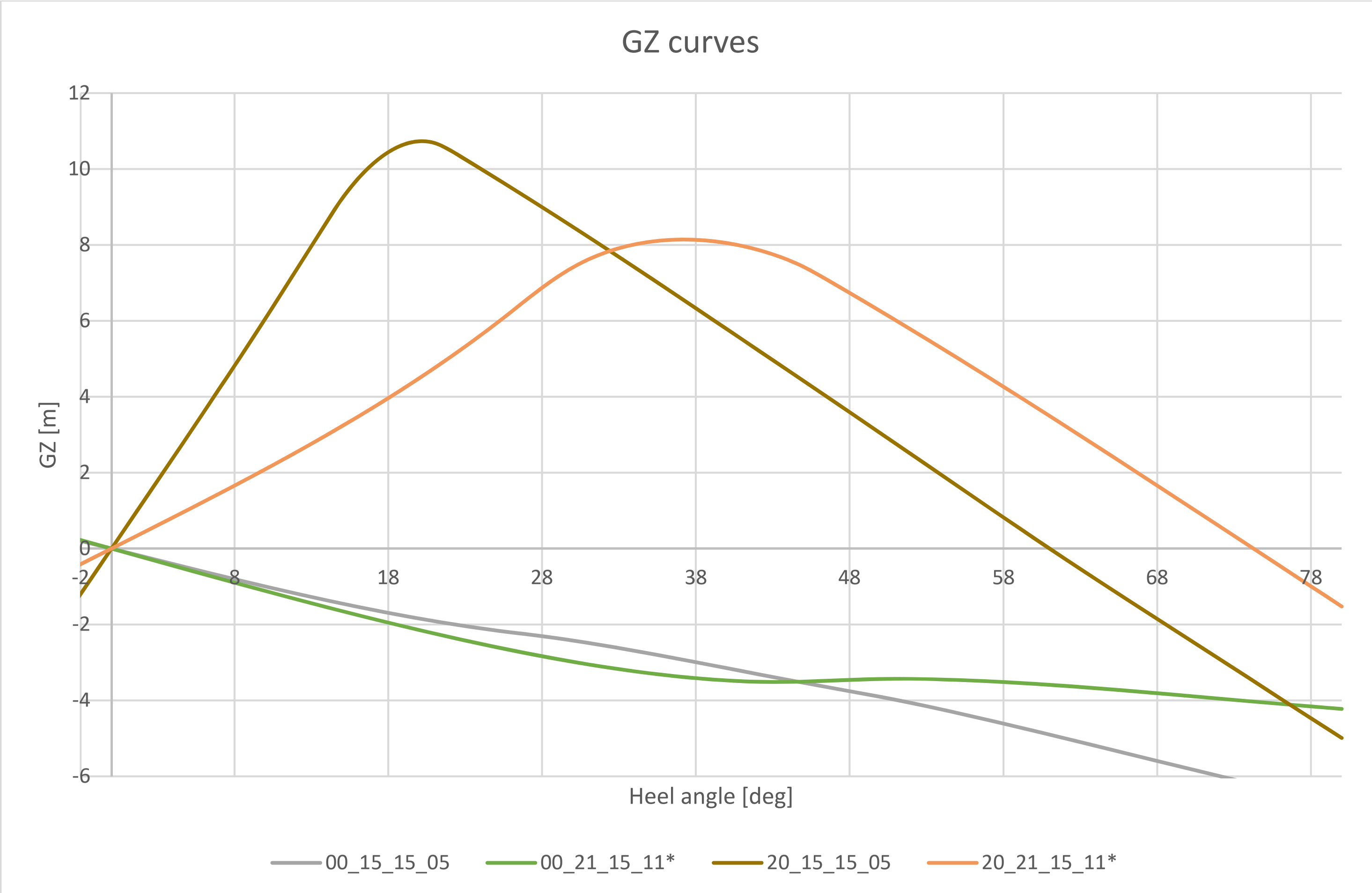
Appendix B

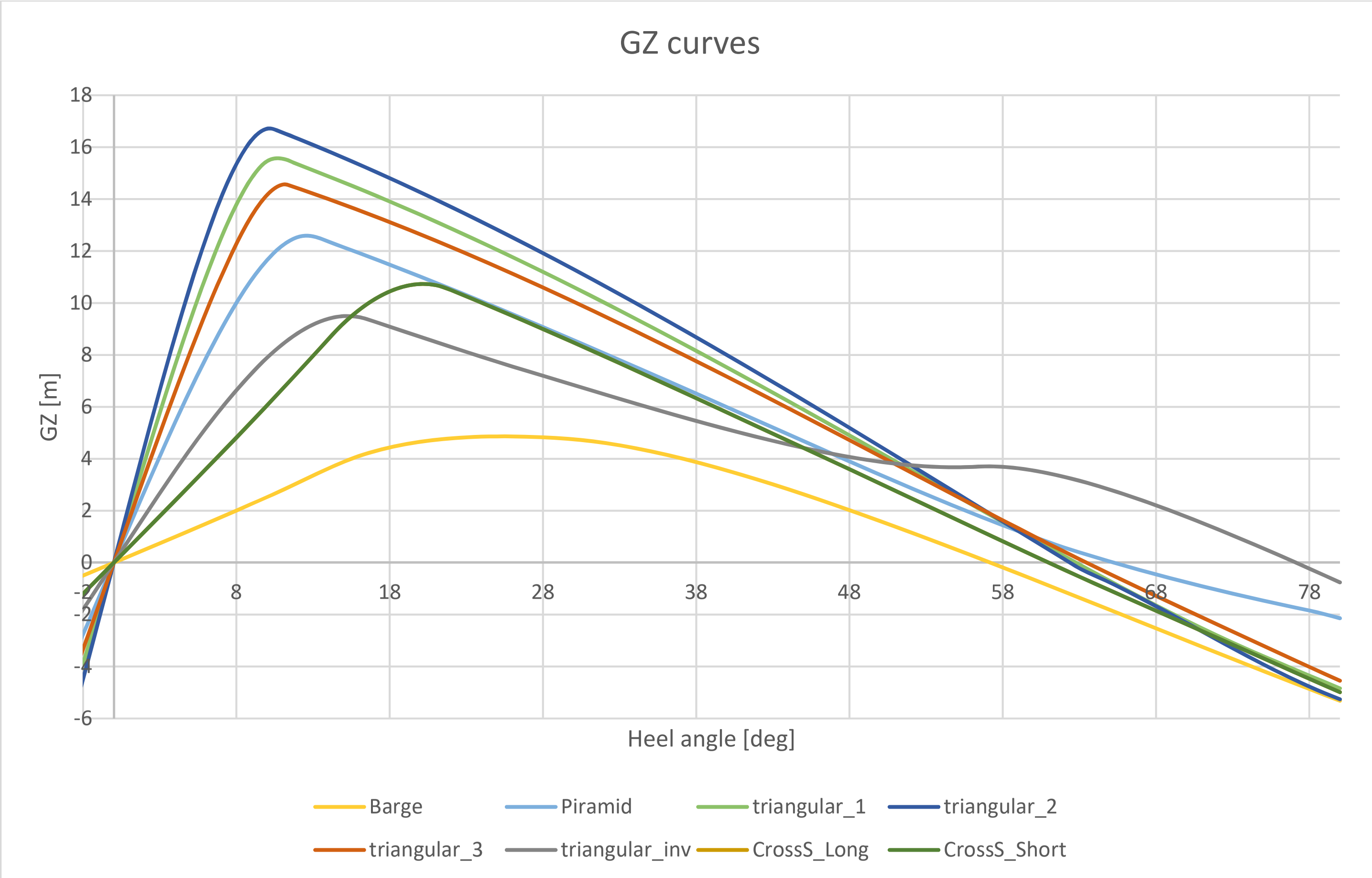
GZ for Box Shape Vessels


GZ curves
GZ [m]
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
8
18
28
38
48
58
68
78
Heel angle [deg]
00_15_15_05
10_15_15_05
20_15_15_05
30_15_15_05


GZ curves
GZ [m]
12
10
8
6
4
2
0
-2
-4
-6
-2
8
18
28
38
48
58
68
78
Heel angle [deg]
00_11_15_05
00_15_15_05
00_21_15_05
20_11_15_05
20_15_15_05
20_21_15_05

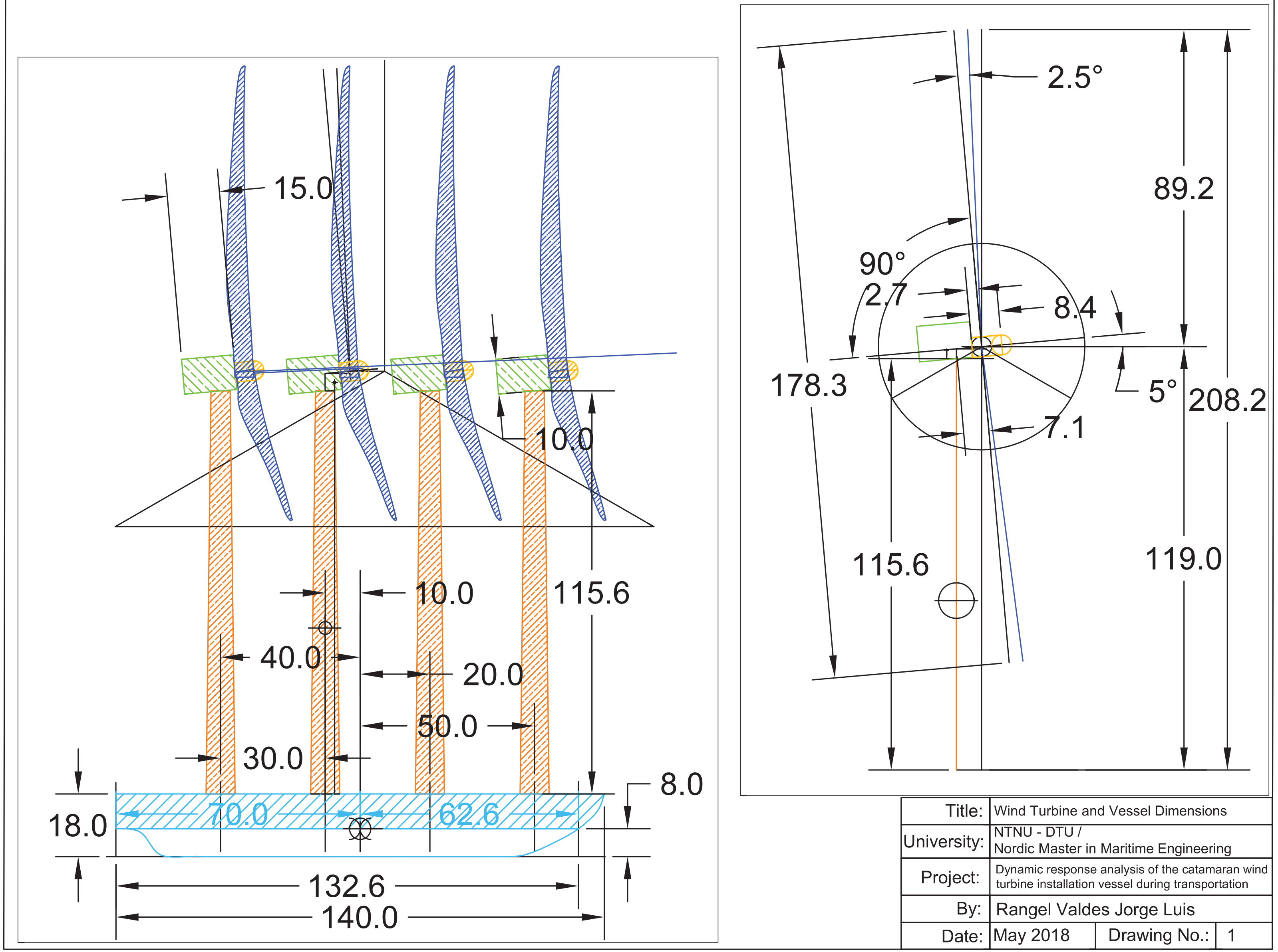

GZ curves
GZ [m]
16
14
12
10
8
6
4
2
0
-2
-4
-6
8
18
28
38
48
58
68
78
Heel angle [deg]
00_15_05_05
00_15_15_05
00_15_20_05
20_15_05_05
20_15_15_05
20_15_20_05
20_15_50_05


GZ curves
GZ [m]
12
10
8
6
4
2
0
-2
-4
-6
-2
8
18
28
38
48
58
68
78
Heel angle [deg]
00_15_15_05
00_21_15_11*
20_15_15_05
20_21_15_11*

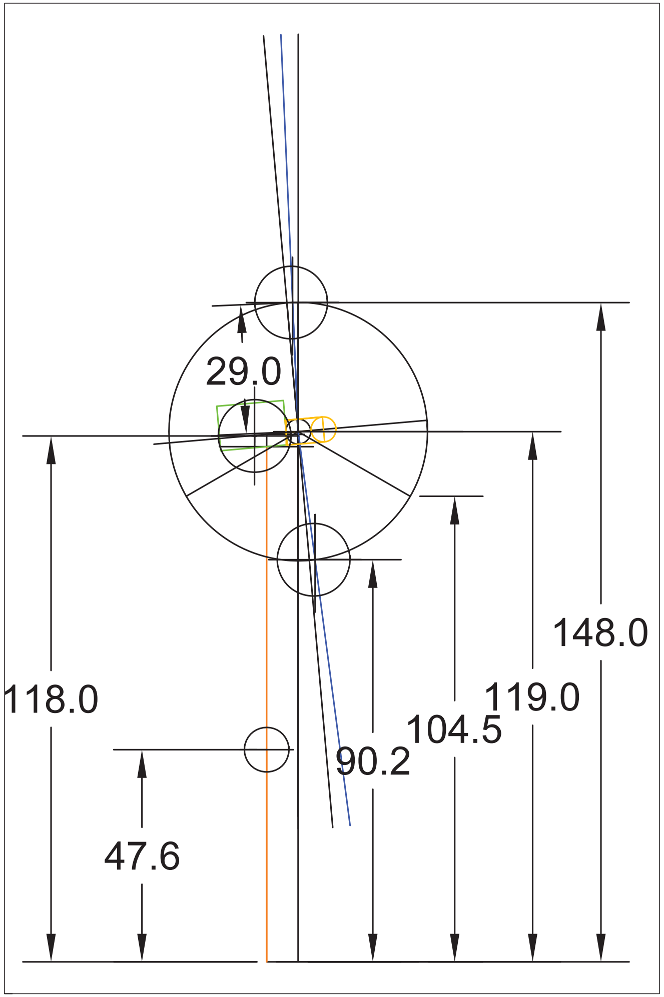

GZ curves
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
GZ [m]
8
18
28
38
48
58
68
78
Heel angle [deg]
Barge
Piramid
triangular_1
triangular_2
triangular_3
triangular_inv
CrossS_Long
CrossS_Short

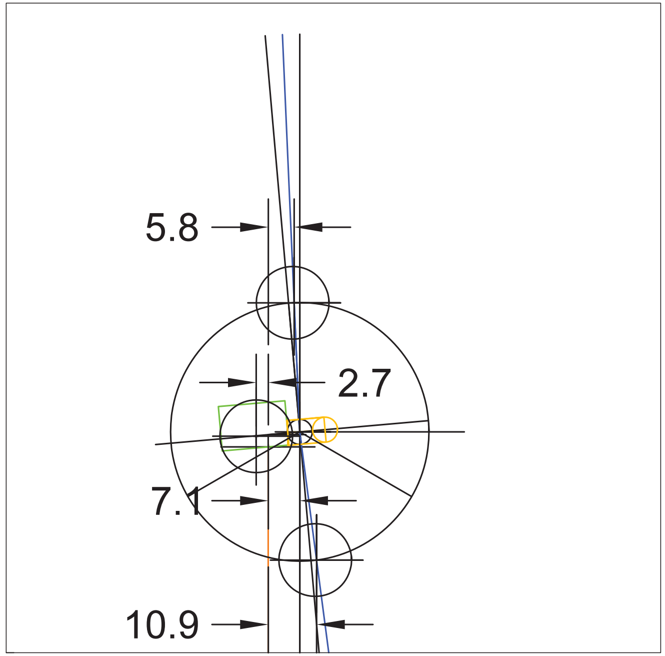
Appendix C

Vessel plans



Title:	Wind Turbine and Vessel Dimensions
University:	NTNU - DTU / Nordic Master in Maritime Engineering
Project:	Dynamic response analysis of the catamaran wind turbine installation vessel during transportation
By:	Rangel Valdes Jorge Luis
Date:	May 2018 — Drawing No.: 1





General wind turbine with origin in tower base				
	mass (Ton)	x (m)	y (m)	z (m)
Blade_1	41.72	5.80	0.00	148.00
Blade_2	41.72	10.90	-25.00	104.50
Blade_3	41.72	10.90	25.00	104.50
Hub	105.52	7.10	0.00	119.00
Nacelle	446.04	-2.70	0.00	118.00
Tower	628.44	0.00	0.00	47.62
Overall	1305.15	0.53	0.00	84.29

Title:	Wind Turbine and Vessel Dimensions		
University:	NTNU - DTU / Nordic Master in Maritime Engineering		
Project:	Dynamic response analysis of the catamaran wind turbine installation vessel during transportation		
By:	Rangel Valdes Jorge Luis		
Date:	May 2018	Drawing No.:	2