Response of the mast and shrouds of a sailboat subjected to wind force

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To my family in Lisbon.

Lisbon, January 2021

Francesco Mauri

ABSTRACT:

The objective of the work is to study the dynamic response of mast and the shrouds of a sailboat subjected to wind force. The performance of the sailing boat is evaluated considering different designs of the mast and shrouds, and finally the best configuration, according to the sails used and the driving force needed is adopted to perform static and dynamic analysis. The main criteria for the design of the mast is the capacity to stand the required sail area (SAR) for the sailboat to sail in good condition and the physical dimension of the sailboat: breadth, length of the hull and position of the boom. The study consists of two main parts: design of the rig system according to the formulation given by the Germanischer Lloyd with the quasi-static analysis on the behavior of the rig for the conditions of sails used and different forces of wind and apparent wind angles. The second part is the dynamic response of the mast and shrouds with the application of a wind spectrum with the comparison of the modal analysis. In the first stage, the wind forces are calculated analytically considering several different configurations of sails and various wind speeds and relative angles, based on the calculations for an example sailboat in *DELFTSHIP* software database. In the second stage, just one sail configuration is chosen, and the time series of wind force are generated using a wind spectrum considering the mean wind speed and direction. Transient responses of the mast and shrouds are numerically calculated using the commercial software *ANSYS*. Dynamic responses of the rig are analyzed combining the dynamic characteristics obtained from a modal analysis.

Keywords:

Sailboat, wind force, SAR determination, mast, shrouds, static equilibrium, dynamic analysis, wind spectrum, modal analysis.

RESUMO:

O objectivo do trabalho é estudar a resposta dinâmica do masto e o brandais de um veleiro submetido à força do vento. O desempenho do veleiro é avaliado considerando configuraçoes design de mastro e brandais, e por fim é adoptada a melhor configuração considerando as velas utilizadas e a força necessariá para movimentar o barco.

O estudo consiste em dua partes, a primeira è o projecto do sistema masto segundo os requisitos da Germanischer Lloyd com a analise quase estatica ao fim de estudar o comportamento do sistema para o estados das velas utilizadas e as diferentes forças de vento e ângulo. A segunda é a resposta dinâmica do sistema do mastro com a appliçao do vento segundo um espectro e depois a comparaçã com a análise modal. Na primeira parte, a força do vento é calculada analiticamente considerando varias condições diferentes de velas e varias velocidades do vento e ângulo relativos, baseando os cálculos num exemplo de veleiro do banco de dados do software DELFTShip. Na segunda parte, apenas uma condição de vela é escolhida e as séries temporais das forças do vento sao geradas usando um espectro de vento considerando a direção e velocidade média do vento. A resposta transitória do sistema mastro sao calculadas numericamente usando o software ANSYS.

Como conclusão, uma analise modal é realizada e a resposta transitoria é comparada.

Keywords:

Veleiro, força do vento, SAR determinação, sistema mastro, equilibrio estatico, analise dinamica, espectro do vento, analise modal.

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

TABLE OF CONTENTS:

LIST OF TABLES:

LIST OF FIGURES:

ACRONYMS:

Main characteristics of the yacht

L_{OA}: Length Over All, is the length measured between the two extremes point of the hull in the longitudinal direction

L_{WL}: Length Water Line, is the most important propriety of a sailboat and is the maximum length of the submerged hull in the longitudinal direction

B_{MAX}: Maximum breadth of the yacht

B_{WL}: Maximum breadth of the yacht at the water line

T: Maximum draft of the yacht when floating

D: Vertical distance from the deepest point f the keel to the sheer line

FB: Free Board of the yacht, vertical distance between the sheer line and the water plane

∇: Volume of Displacement

Δ: Weight of the yacht

B: Centre of buoyancy, the center of gravity of the displaced volume of water

G: Centre of gravity of the yacht

Sail plan

SAR: Sail area of reference

P: Height of the mainsail

I: Height of fore triangle

E: Base of the mainsail

J: Base of fore triangle

CoE_m: Centre of effort of the mainsail

CoE_f: Centre of effort of the foresail

CoE_s: Centre of effort of the spinnaker

CLR: The center of lateral resistance of the underwater body

A_m: Mainsail area

A_f: Foresail area

A_j: Spinnaker area

Design and construction

RM_{design}: Design righting moment

SFC_m: Side force coefficient mainsail

$SFCA_f$: Side force coefficient fore sail

F_{tm}: Transverse force of the mainsail

F_{im}: Mainsail load distribution

F_{tf}: Transverse force of the foresail

F_{if}: Foresail load distribution

F_{ts}: Transverse force of the spinnaker

F_{is}: Spinnaker load distribution

F_{ml}: Mainsail leech load

F_{mhy}: Mainsail halyards

F_{fhy}: Foresail halyards

F_{hs}: Head stay working load

Vn: Vertical shroud

Dn: Diagonal shroud

Wind spectra

S_U (f): Spectral density

L_U: Integral length scale

σ_u: Distribution of the standard deviation

f: Frequency domain

SYMBOLOGY:

FEM: Finite Element Method

DNV: Det Norske Veritas

RINa: Registro Italiano Navale

ITTC: International Towing Tank Conference

1. INTRODUCTION

1.1 Background and Motivation

The great distribution of sailing for amateurs lead an even increasing number of fans of getting in touch and being interested by the world of the sailing yacht. Not only for recreational reasons but also for the interesting physics that drive a yacht in the ocean with the only force of the wind and that is the reason why I consider this thesis important to me because it is matching my studies of naval engineering and my passion of the ocean and sailing. The thesis is possible to be summarized in three main parts that want to give the main idea of the work done.

The first one is the generation of the sailboat and the entire rig. To start the project the software *DELFTShip* is used, selecting a hull from its database. The dimensions of the hull are of 50 *feet* in order to give the study for small and leisure sailboat. In the software small variations of the hull and the weight distribution of its components are performed. After this part is concluded the static and hydrodynamic properties are studied, and useful will be the knowledge of the use of the software *Archimedes*, which will perform the static analysis of the hull. For each angle of tilt, the software will return the heeling moment that the hull needs to get the angle of heel. So, this part is the base to perform the design and dimensioning of the entire rig, because according to the reference [1], the rig will be designed for the static righting moment of the yacht at full displacement with a heel angle of 30°. The part of the design of the mast first is focusing the geometrical sketch of the mast according to the main dimension of the sailboat and its aim and secondly to the scantling of the equipment required.

After this part is done, the quasi-static analysis will carry on. For the dimensioning of the rig, the forces were applied directly to the mast tube knowing the righting moment of the yacht for the condition of 30° of heel. Now, the wind speed is the beginning of this study. With the *G. Hazen* model of the reference [2], for different wind speed and apparent wind angle the side and driving force generated on the three different types of sails considered are computed: mainsail, jib and spinnaker. The quasi-static analysis is performed varying the apparent wind angle and wind speed with a $\Delta T\ of\ 1\ sec$, and kept for the same time step. Step of $\Delta T\ of\ 2\ sec$ is used for the spinnaker condition while changing the apparent wind angle. The main idea of the quasi-static analysis is to get the maximum stresses possible in the structure and the study of its behavior.

As last analysis, the dynamic response of the rig structure is performed. In this analysis, the wind force is generated with a wind spectrum following the guideline of the reference [1]. The spectrum in frequency domain will be turned in time domain. The analysis will be performed for *1000 s* in order to get a good resolution of the results.

As a conclusion, the recorded displacement of the mast tube will convert, with a Fourier transformation, in frequency domain and the peaks of the graph compared with the modal analysis to find which mode gives the most contribution.

1.2 Objectives

The thesis is divided into different parts and each part has different objectives. First, the design of the mast rig, spreaders and shrouds will be performed, different configuration sails will be analyzed in order to get the perfect match for the rig to support wind loads for the type of yacht considered. Then, with the rig mast configuration adopted, the quasi-static analysis will be carried on to study the behavior of the structure and check stresses, strain and deformations of each part of the rig. This analysis will lead to increase diameters of some shrouds. As final, the dynamic study of the rig is performed. First, the rig is subjected to a modal analysis that wants to find the natural modes of the structure; three modes of vibrating in longitudinal and transversal plane are found. Secondly, the dynamic response of mast and the shrouds of a sailboat is done applying to the structure the time domain representation of the wind spectrum generated. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. The dynamic analysis wants to investigate the contribution of the natural modes in the response of the rig, and see which mode contributes more in the response of the rig system.

1.3 Structure of the Thesis

The thesis is organized and divided into five chapters with relative subchapters and respective appendices.

- **Chapter 1** is the introduction in which the main topic and goals of the thesis will be discussed. This first part wants to give the main idea of the work.
- **Chapter 2** is dedicated to the state of art, regarding the previous work and studies in order to be able to perform the quasi-static and dynamic analysis and the response of the structure.
- **Chapter 3** is the part of the thesis in which methods assumptions and equation are presented in order to perform the study of the topic of the thesis.
- **Chapter 4** is the numerical computation of the thesis. Chapter 4 gives the numerical results obtained for the problem.
- **Chapter 5** contains the conclusion of the work with some ideas for future work.

2. LITERATURE REVIEW

2.1 Yacht definitions

The hull of a sailboat is a tapered solid with section and curvatures that change from the bow to the stern, is symmetric regarding the vertical plane that passes by the longitudinal centerline. The water plane divides the hull into two main parts: the part that in normal conditions stays outside the water is the free board and the other one is named submerged area.

In the submerged area of a sailboat two main parts stand: the keel and the appendage. The hull appendage includes the sail keel and the rudder. The sail keel can be ballasted and in this can have two functions: opposing the lateral force of the wind and reducing the center of gravity of the yacht. If it is void of ballast just the first function is performed. The rudder is an appendage that can turn on its axis and is used to control the direction of motion of the sailboat [3]. [2].

The main linear dimensions of the hull are:

L_{OA}: Length Over All, is the length measured between the two extreme points of the hull in the longitudinal direction.

L_{WL}: Length Water Line, is the most important propriety of a sailboat and is the maximum length of the submerged hull in the longitudinal direction.

B_{MAX}: Maximum breadth of the yacht.

B_{WL}: Maximum breadth of the yacht at the water line.

T: Maximum draft of the yacht when floating.

D: Vertical distance from the deepest point f the keel to the sheer line.

FB: Free Board of the yacht, vertical distance between the sheer line and the water plane.

∇: Volume of Displacement.

Δ: Weight of the yacht.

B: Centre of buoyancy, the center of gravity of the displaced volume of water.

G: Centre of gravity of the yacht.

All the formulations and main ideas to develop o sailboat from zero are presented in [3] and [2]. While in [4] a redesign of a Dark Harbor 17.5 was proposed. First, an initial design evaluation will be performed to assess the characteristic of the original yacht, regarding hydrostatics, hydrodynamics, structural arrangement and comfort. Finally, the new design will be compared to the original one, allowing to evaluate the challenges of design modernization and the impact of contemporary requirements on a traditional design.

When developing a sailing boat, the design and scantling of the rigging system supporting the sails is often a critical part of the project. Those rigging systems (mast and standing rigging) are composed of cables and beams subjected to high compression loads and large deformations. One of the most difficult tasks for a rig designer is to estimate the maximum loading condition for a rig. These loads determine the mast tube dimensions such as wall thickness and the stay diameters. In rig dimensioning procedures it is a common practice to take the righting moment of the sailing yacht at 30 degrees as a base to compute the compression forces in the mast tube and the tension forces in the standing rigging. With FEA performed on yacht rigs it is possible to determine the efforts in all parts of the rig and to predict deformations of the mast and the standing rigging. This is what is presented in [5]; the main idea of the paper is follow in the first part of the thesis.

2.2 Static and dynamic of a sailboat

The trim assumed by a sailboat is the result of all the components of the forces involved, those of a hydrodynamic nature and those from a physics point of view. Without going into the details, a boat is in balance when the buoyancy compensates its weight [6].

When a boat is driven from the force of the wind, its static balance varies and the trim is influenced not only by the factors described above, but also by the lift of the hull that is generated by the speed of the boat. This difference is easily to be understood by the different behaviour of a displacement hull from a planning one. Where for a planning hull its equilibrium condition is given by the sum of three components: centre of gravity, point of pressure of the hydrodynamic force or lift and the hydrostatic buoy of the hull.

When a hull is planning these two components mentioned before change considering that the hydrodynamic pressure varies exponentially with the hull's speed, also modifying the position of the centre of buoy.

[7] presents a review of the physical phenomena that govern the motion of a sailing yacht. Motion is determined by force, and the forces on a sailing yacht depend on the interactions of the hull and keel of the yacht with the water and on the interactions of the sail or sails of the yacht with the air.

2.3 Stability of a sailboat

Floating is not everything. It is evident that a fundamental characteristic of a hull is to keep its trim. This, in addition to obvious reasons of comfort and safety, is also important for the efficiency of the advance and evolutionary capabilities.

Placing a boat in an initial state of equilibrium, its tendency to return or not to its initial position after the transient action of a disturbing force is defined as "static stability". Considering the cross section of a boat, the hydrostatic force is the result of all the forces due to the exercise of the fluid's pressure on the submerged part of the hull. This resultant is applied to a geometric point, the "centre of buoy". The other force to consider is the weight force applied to the boat's centre of gravity. If the hull rotates along the longitudinal axis, or "roll" axis, in its submerged part a different profile of the hydrostatic pressure takes part. The resultant of this force is always applied to the centre of buoy, which is moved. In this condition, the weight force is applied to the centre of gravity and the hydrostatic forces are no longer aligned along the same axis and therefore show a moment that tends to make the system rotate [7].

To understand the dynamic behaviour of the boat in this condition, a new component must be introduced: the "metacentre" [8]. This is identified by the intersection of the axis of symmetry of the hull with a vertical line passing through the centre of the hull; as long as the metacentre remains above the centre of gravity, the moment will tend to reduce the roll angle so, to bring the boat to its normal condition of equilibrium. On the other hand, when the metacentre comes to be below the centre of gravity, the effect of the moment will increase the roll angle with the inevitable consequence of the boat overturning.

The greater is the distance from the metacentre to the centre of gravity, the more stable the boat will be. Given that the first purpose of a boat is to stay afloat, naval projects pursue the goal of positive static stability, and do so according to two strategies: through "shape stability" or by "weight stability". In both cases, the idea is to increase the arm of the righting moment and the height of the metacentre. With the shape stability, the effect is obtained by accentuating the transverse development of the hull section. Thus, even for small roll angles, the centre of buoy moves significantly away from the centre of gravity. With the weight stability, instead, an attempt is made to push the center of gravity as down as possible in order to increase its vertical distance from the metacentre. This is done easily by ballasting the keel with high specific weight materials.

The book [9] intends to provide theoretical base for the design, manufacture and operation of sailing craft. The main part is the sails design compared with the hull hydrodynamic. Sailing boat has to operate at the interface of two fluids, air and water, deriving propulsion from the former and support from the latter.

2.4 Lift of a wing

What is the lift that makes a boat sail upwind? The term has aeronautical origin and, in that context, indicates the force which the wing of an aircraft is subjected in a direction perpendicular to the air flow incident on it. In nautical context, they are sails, not wings with a wind coming from a small angle of attack, a total aerodynamic force acts on the sail approximately perpendicular to its surface; the transverse component to the wind is precisely the lift.

When the wind flows around the surface of a sail, the particles of the fluid move varying speeds depending on the position: faster on the leeward side than the upwind. The Bernoulli equation relates the pressure of a fluid with the local velocity of its particles; by integrating the local variations of speed, and therefore of pressure, over the entire surface of the sail, the total aerodynamic force is determined.

In more physical terms, the air passing upwind of the sail endure a compression caused by the deflection imposed by the sails; on the leeward side a depression zone is created, so this side is subjected to a suction effect. The sail induces a deviation of the wind from its original direction, and consequently, by the third principle of dynamics, this deviation of the flow produces the aerodynamic force on the sail itself, which is the lift. In other words, the lift is the variation of the perpendicular component of the wind momentum. But, in reality the phenomenon is more complicated. It can be resumed that in a gas flow the principles of conservation of momentum, energy and mass must be applied.

The Bernoulli equation is derived by imposing the principle of conservation of energy, while Newton's law is derived from the conservation of momentum. The mass conservation introduces a further complexity to aerodynamic issues; the air is deflected from the windward side of the sail but, surprisingly enough, also downwind.

For a fluid, the simultaneous conservation of momentum, energy and mass is synthesized by a set of general equations: the Euler equations, a system of partial differential equations that describe the phenomenon. If, for particular study conditions, it is necessary to include viscosity phenomena, reference should be made to the Navier-Stokes equations, because the Euler equations are an approximation. In this way, the system of equations is of such complexity that it does not to allow to determine, in general, an exact analytical solution.

But, focusing on the sails, what matters is that for some basic principles of physics a force is created in a direction perpendicular to the wind: it is what allows a sailboat to move forward. In reality, what matters for the propulsive force for navigation, is the component of the total aerodynamic force produced by the sail projected in the direction of the boat’s advancement [8].

However, if the sailboat receives the wind from the bow, the angle of attack with the sail is zero, the sail flies like a flag: lift and propulsive force are zero. On the other hand, if the wind has a sufficient inclination, propulsive force is produced by adjusting the sails with a correct angle of attack.

The angle of attack of the sail is a critical parameter: continuing to haul so, increasing the angle between the wind and the sail, the propulsive component is reduced by increasing the transverse leeway and heel of the sailboat. Exceeding a certain angle of attack there is a sudden and substantial loss of lift due to the detachment of the leeward air’s streams from the sail, passing from a laminar to a turbulent system. At this point, the sail loses its propulsive effect to assume a drag effect. However, the drag effect is not necessarily negative; on the contrary, it is fundamental in other regimes, such as stern sailing.

Another important study regarding the lift of a wing is presented in [10]. In the paper the most important and useful results of research on the aerodynamics of wing sections at subcritical speeds are presented. [11] presents the fluid-structure interaction analysis of deformation of sail of 30-foot yacht.

2.5 Rig design

The function of a sailing yacht rig is to support the sails used to propel the yacht. To maximise the yacht’s stability and its sail carrying capacity, the rig should be as light as possible, with the centre of gravity as low as possible. At the same time, the profile has to be minimized to reduce drag and the disturbance on the airflow around the sails. On the other hand, the rig should have a certain ability to deform in a controllable manner, to trim the sails without losing the load carrying ability. These requirements make the design of a rig a very interesting challenge [12, 13].

One of the most difficult tasks for a rig designer is to estimate the maximum loading condition for a rig. These loads determine the mast tube dimensions such as wall thickness and the stay diameters. The constant drive for better sailing performance pushes the design to the limits, even for cruising yachts. In combination with the growing use of composite materials for mast and rigging, this asks for a new way of rig design. A sailing yacht rig might seem a very simple structure but in reality it is not. It behaves in a very complex way every time different.

The current design methods used are based on analytical approaches. In this method, relatively high and often also inexplicable safety factors are used to take into account design uncertainties by using models that are more sophisticated it is possible to reduce the various safety factors [14].

As an alternative check for the current analytical approach is the use of a finite element analyses (FEA) program. These powerful tools are very useful to analyse the nonlinear behaviour of rigs, but their reliability heavily depends on the analysis method and the accuracy of the loading input.

A rig can be divided in a mast tube and standing rigging supporting the mast. The rigging consists of longitudinal and transverse stays. The whole structure is loaded in the following ways:

- Distributed forces and point loads from the sails are acting on the mast and forestay.
- Point loads are acting on the mast at the attachments of stays, spreaders, boom, pole and other equipment.
- The dynamic behaviour of the yacht causes inertia forces.

The behaviour of a rig depends on all these loads that vary for the different sail conditions.

All rig design calculation procedures found in literature are more or less based on the Skene method. The method takes note from the "Safe Working Angle (SWA)" which, generally represents a heeling angle of 30° [15]. A possible scenario for the occurrence of the local buckling of the wall of the thin-walled aluminium mast is analysed in [16]. The possible occurrence of buckling is avoided using safety factors to take into account design uncertainties. After the design of the mast rig, a FEM analysis the measures of the forces are performed in [17].

2.6 Wind spectrum

Wind speed varies with time. It also varies with the height above the ground or the height above the sea surface. Wind speed static is used as a basis for representation of long-term and short-term wind condition. Long-term is usually referred to 10 years or more. Short-term commonly averaging time is 1, 10, 60 minutes and 10 meters of height.

The 10-minute mean wind speed is a measure of the intensity of the wind. The standard deviation σ_U is a measure of the variability of the wind speed about the mean. When special conditions like hurricanes, cyclones and typhoons occur, a representation of the wind climates in 10-minute may be insufficient.

The long-term probability distribution for the wind climate parameters U_{10} and σ_U that are derived from available data can be represented in terms of generic distributions or in terms of scatter diagrams. An example of a generic distribution representation consists of a Weibull distribution for the arbitrary 10-minute mean wind speed U_{10} in conjunction with a lognormal distribution of σ_U conditional on U_{10} . A scatter diagram provides the frequency of occurrence of given pairs (U_{10}, σ_U) in a given discretisation of the (U_{10}, σ_U) space. Unless data indicate otherwise, a Weibull distribution can be assumed for the arbitrary 10- minute mean wind speed U_{10} in a given height z above the ground or above the sea water level.

The wind speed profile represents the variation of the mean wind speed with height above the ground or above the still water level, whichever is applicable. When terrain conditions and atmospheric stability conditions are not complex, the wind speed profile may be represented by an idealized model profile. The most commonly applied wind profile models are the logarithmic profile model, the power law model and the Frøya model.

The natural variability of the wind speed about the mean wind speed U_{10} in a 10-minute period is known as turbulence and is characterized by the standard deviation σ_U. For given value of U_{10}, the standard deviation σU of the wind speed exhibits a natural variability from one 10-minute period to another [1]

Wind spectra

Short-term stationary wind conditions may be described by a wind spectrum. Site-specific spectral densities of the wind speed process can be determined from available measured wind data.

When site-specific spectral densities based on measured data are used, the following requirement to the energy content in the high frequency range should be fulfilled, unless data indicate otherwise: The spectral density $S_U(f)$ shall asymptotically approach the following form as the frequency f in the high frequency range increases

$$S_U(f) = 0.14 * \sigma_U{}^2 * \left(\frac{L_u}{U_{10}}\right)^{-\frac{2}{3}} * f^{-5/3}$$

in which L_u is the integral of the scale length.

Unless data indicate otherwise, the spectral density of the wind speed process may be represented by a model spectrum. Several model spectra exist. They generally agree in the high frequency range, whereas large differences exist in the low frequency range. Most available model spectra are calibrated to wind data obtained over land. Only a few are calibrated to wind data obtained over water. Model spectra are often expressed in terms of the integral length scale of the wind speed process. The most commonly used model spectra with length scales are: Davenport spectrum, Kaimal spectrum, Harris spectrum, Simiu and Leigh spectrum, Ochi and Shin spectrum, Frøya model spectral density. Various explanation and example of the wind were given in [18]. From its generation to all the possible solution to schematize it.

A good example of the use of the wind spectrum is given in [19], where stochastic wind and wave times series are generated from a given spectrum. The Kaimal spectrum is used for wind time series, and Jonswap spectrum is used for wave times series.

2.7 Operational vibration-Based response estimation

In the paper of the reference [7], the wind spectrum is used to study the fatigue of an offshore wind turbine. The comparison of the generation of the wind spectrum was found to be useful according to the Kaimal spectrum and the idea of the comparison of the modal analysis with the response of the wind turbine structure. Wind force is determined on the basis of the actuator disc, where a 1D free field turbulence is simulated on the basis of the spectral properties of a Kaimal power density spectrum as a function of frequency, same study is done in [20]. Figure 2.1 shows the Kaimal spectrum adopted for the generation of the wind force signal of the paper. The spectrum reveals a main energy contribution from the frequencies below 1 Hz. Assuming a random phase distribution, and a cut-off frequency of 3 Hz, a wind force signal of 546 s is generated. After the wind spectrum is generated, first wind speed and after force generated in time domain. Figure 2.2 depicts a 100 s window of this time signal. The finite element model does not include a detailed rotor representation, the total wind force is assumed to act concentrated at the rotor nacelle assembly at the tower top. It should be noted that, despite the turbulence frequency cut-off, the wind force signal contains higher frequency contributions. The images presented are taken from [7]

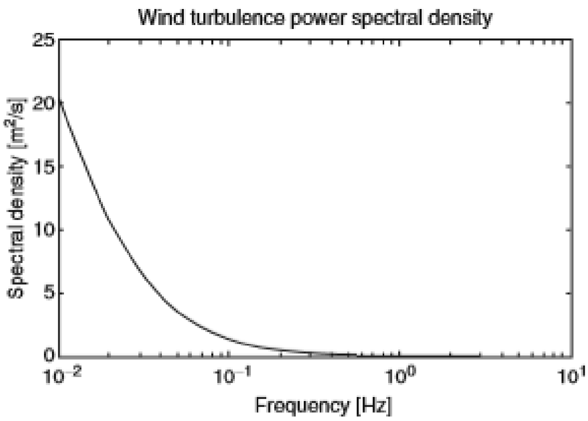


Figure 2.1: Kaimal wind spectrum

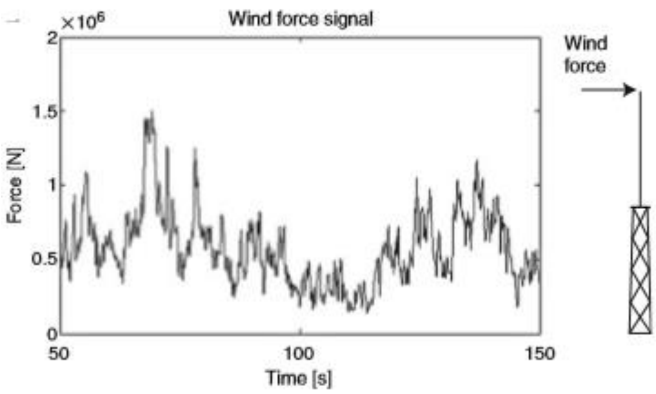
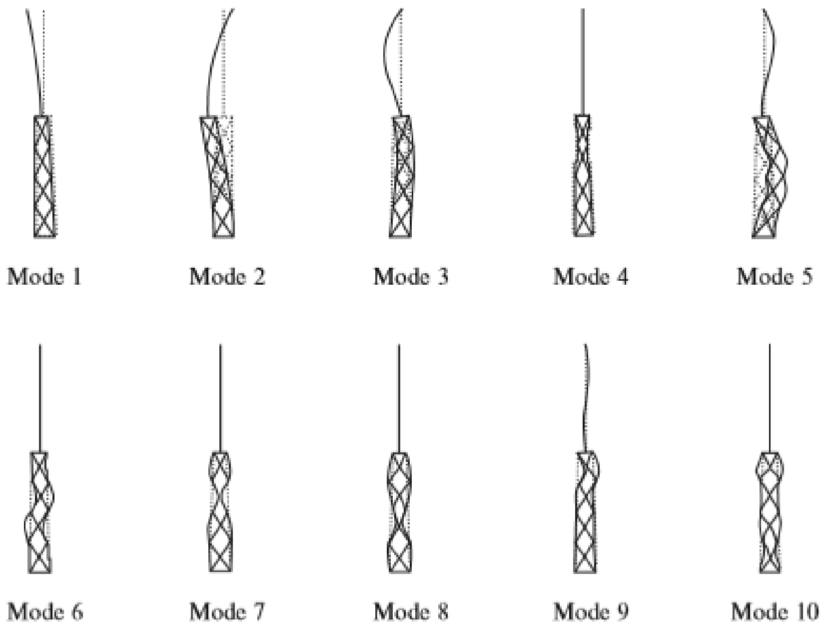


Figure 2.2: Time series

The study of the response of the wind turbine tower after the application of the wind force is then compared with the modal analysis, displayed in Figure 2.3. This part of the paper has been considered a good idea for the later study of the thesis where the response of the rig system is compared with the modal analysis after the application of the time series wind, generated from the Kaimal spectrum.



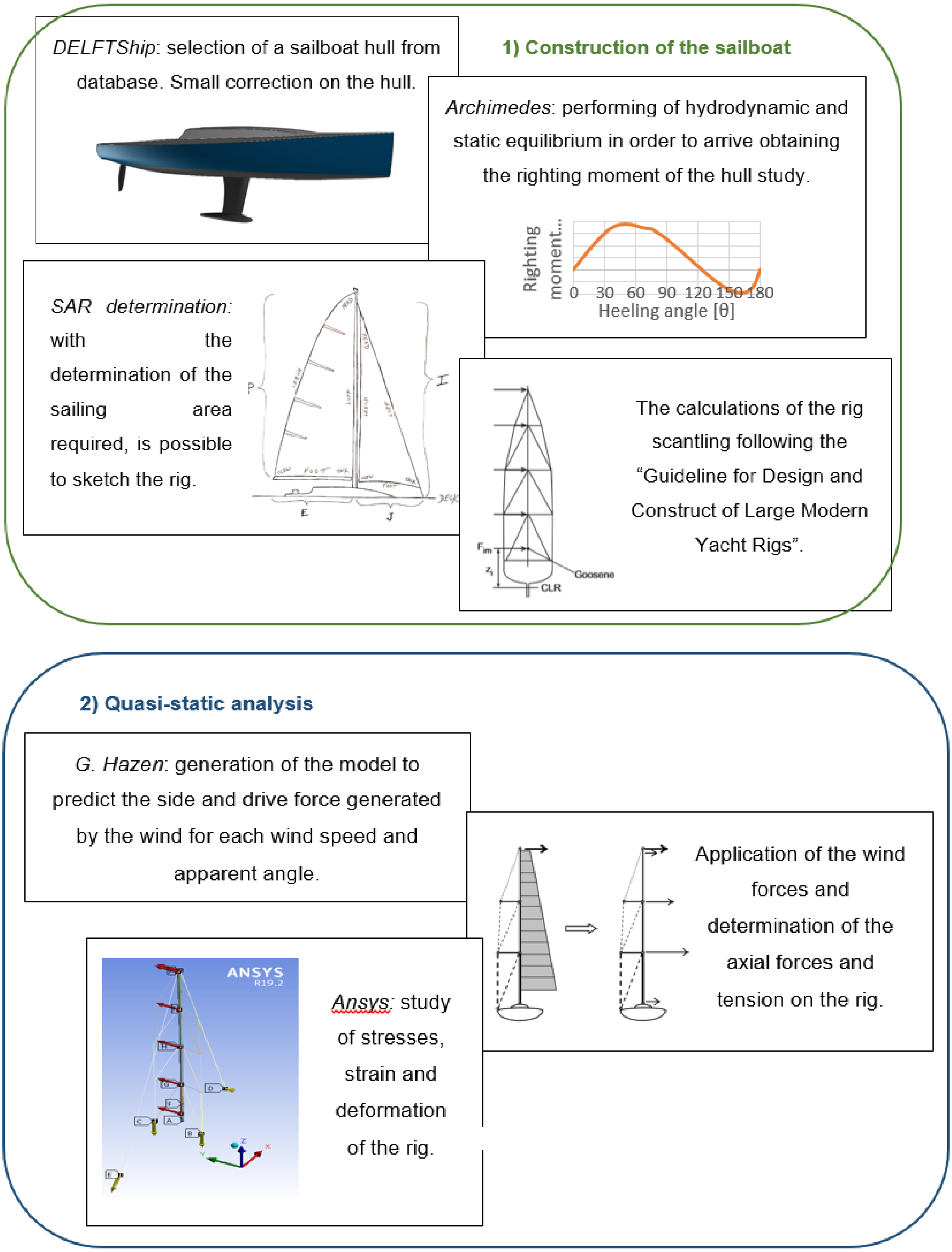
No.	Natural frequency [Hz]	Description
1	0.364	First global lateral mode
2	1.07	Second global lateral mode
3	4.89	Third global lateral mode
4	6.20	First global vertical mode
5	6.77	Fourth global lateral mode
6	10.4	Lateral jacket mode (second and third frame from top – in-phase
7	10.4	Local lateral jacket mode (second frame from top – anti-phase)
8	10.9	Local lateral jacket mode (third frame from top – anti-phase)
9	12.6	Local lateral jacket mode (first frame from top – in-phase)
10	13.8	Local lateral jacket mode (first and fourth frame from top – anti-phase)

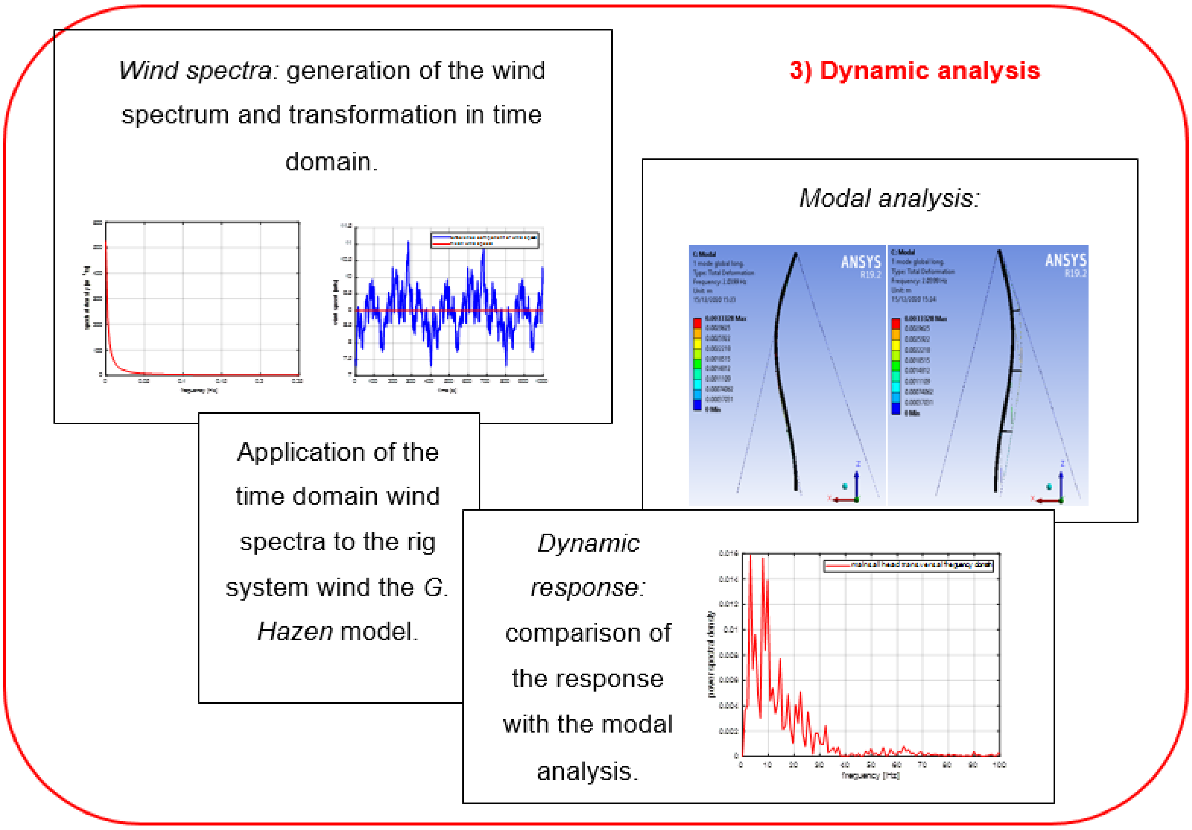
Figure 2.3: Modal analysis of the wind turbine tower

The Kaimal spectrum is used in [21] to generate a wind time series and use it for the simulation of a wind turbine.

3. METHODOLOGY

The main sketch of the thesis can be simply schematized in these three parts reported in the graph here.





3.1 Physics of a sail boat

3.1.1 Overview

A sailboat is a complex machine, which interacts simultaneously with two different fluids: air and water. The driving force of a sailboat is generated by the sails; working deviating the airflow (wind) and generating a pressure difference that will generate the required lift. Water will support the boat generating Archimedean force (or if the boat is fast enough, the hull will generate a lift, in that case, the boat is planning).

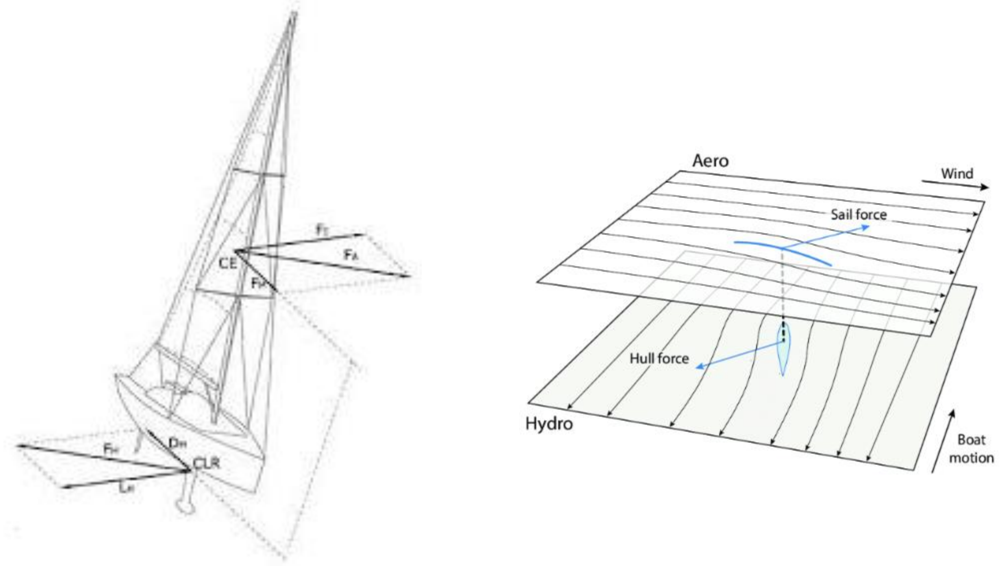


Figure 3.1: Principle of equilibrium between aero and hydro forces [9]

As seen in Figure 3.1, the wind is an essential force for the motion of a sailboat. Another important characteristic of a sailboat is that it can only move in the direction of the keel, which is also the direction of the centerline. After the wind hits the sails, the condition of equilibrium between the driving force of the wind and the resistance of the sailboat is not reached immediately, but requires a period of time in which there is an adaptation of the system. When the two forces are equal and opposed, the total force acting of the sailboat is zero, and it stops accelerating and starts sailing at constant speed. This condition is the same, even when the wind is getting stronger or reducing its force.

For the study carried out, the sailboat is considered in condition of equilibrium for different wind forces.

3.1.2 Static of the sailboat

The fundamental requirement of any boat is the buoyancy and this force came out with the *Archimede theory.* The application of the two forces, buoyancy and weight, are represented in Figure 3.2. This does allow to get the relation between the displacement and the volume, but also to check the sailboat to buoy in the right trim. For the longitudinal symmetry, it is impossible that a sailboat can be buoy skidded, unless external forces that may generate torque are applied.

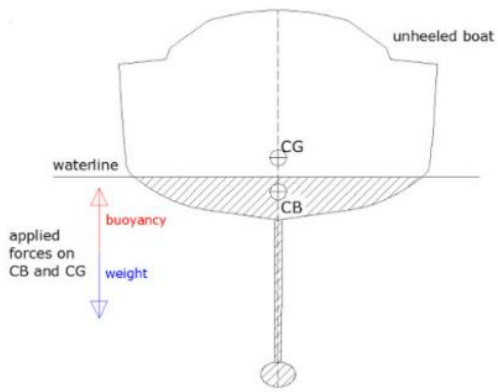


Figure 3.2: Buoyancy of a sailboat [9]

The sailboat is subjected to two forces, equal and opposed that may create a torque: the displacement Δ that have as application point the center of gravity C_G, and the buoyancy $\gamma\nabla$ that acts in the center of volume C_B. The center of gravity and center of buoyancy are things completely different: the center of gravity depends on the weight of all sailboats; the center of buoyancy is connected to the portions of the volume of the hull. Since the forces will not create a torque, the harm of the two forces has to be zero, i.e. they act on the same line of action.

3.1.2 Stability of the sailboat

To carry out the study of the rig system, it is fundamental to be aware of the stability of the sailboat, Figure 3.2. Regarding the stability of a boat, it means the ability to oppose any external force. In general, a boat can tilt in any direction and this is interpreted as the result of a transverse and a longitudinal rotation. In the case of study, only the transversal rotation is taken into account. In the absence of any external force, a boat floats under the action of two equal and opposite forces, the displacement that acts in the center of gravity, and the hydrostatic thrust applied in the center of the flotation.

If the boat is slightly inclined in any direction with respect to the rest position, it spontaneously returns to the initial position when the external force ceases. This condition is named stable equilibrium. If, always chased at the same inclination, the boat stays in the new position, this one is the condition of unstable equilibrium. Finally, if following a modest inclination, the boat moves further and further away from the initial position, then you are facing a torque that may capsize the sailboat [22].

Normally a sailboat, as all the ships, has the C_G over the C_B. For this characteristic, a typical situation is determined, briefly explained here below. Initially for moderate heeling angles, there is a straightening pair, which grows progressively to a maximum and then decreases when the center of gravity moves significantly to the right for more pronounced skidding. When the center of gravity C_G is on the vertical of the C_B, of the heeled boat, the couple cancels, then changes their sign and becomes overturning, for even greater angles.

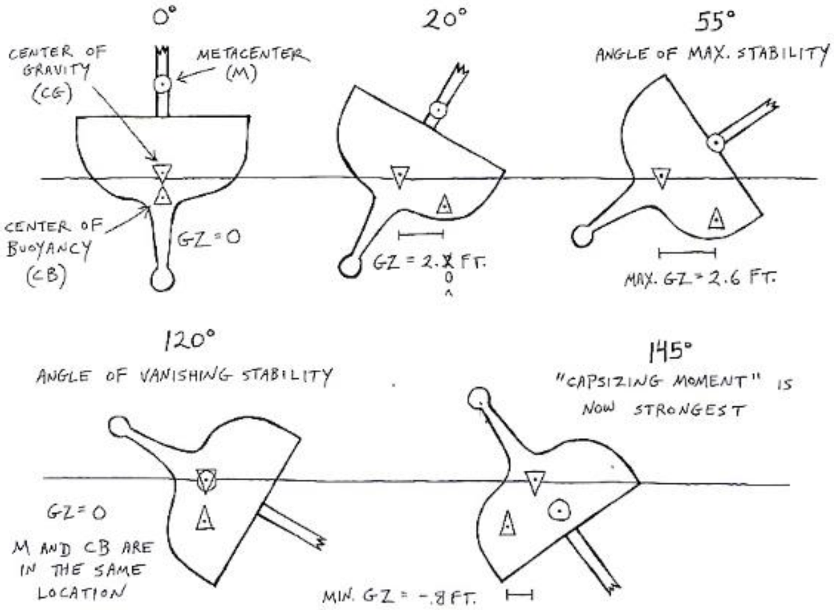


Figure 3.3: Stability of a sailboat

Going through a more detailed approach, a sailboat with the C_G over the C_B is taken into account for the case of study, and the new situation is observed if it transversally tilts with a small angle of heeling. The center of gravity, whose position is determined by the weight distribution of the entire boat, remains fixed in the same position, while the center of buoyancy moves, having changed the portion of the immersed hull moving tis position from B_0 to B. At this point, the two forces P and S are no more on the same vertical and so they produce a torque of stability, its harm is the distance $\overline{GZ}$ between the two lines of action of respectably G and B. Since the weight of the sailboat is known, just need to relate $\overline{GZ}$ with the geometrical characteristic of the hull, in order to get the stability of the sailboat.

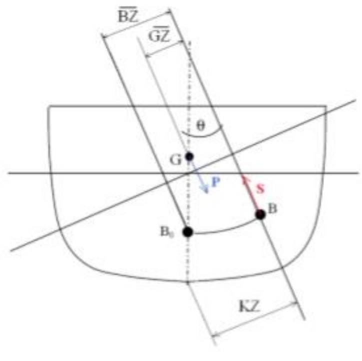


Figure 3.4: Main characteristics of the stability study [22]

Important for the study is the metacentric point ($M_{transversal}$), the intersection between the vertical that goes through B, with the line of symmetry of the hull going through B_0 and G, and the distance between the metacentric point and the keel line is named $\overline{MZ}$.

It results that:

$$\overline{GZ} = (\overline{MZ} - \overline{C_G Z}) * SIN(\theta) \tag{3.1}$$

It is seen that the righting moment is given as:

$$RM_{(\theta)} = \overline{GZ} * \Delta \tag{3.2}$$

In a final analysis it is noticed that the metacentric point is the point where the hull revolves around of an angle θ.

The position of the metacentric point compared to the center of gravity identifies the type of balance to which the boat is subjected: with the position of M over C_G it has stable equilibrium. With M in the same position of C_G it is facing indifferent equilibrium and with M above C_G it is facing with unstable equilibrium, as a small rotation immediately causes the appearance of a negative torque that is a skid.

3.2 SAR determination

The complete project of a propulsive plan of a sailboat can be schematized in the following way:

- Determination of the sail area of reference SAR;
- Choice of the type of equipment;
- Drawing of the sail plan;
- Mechanical proportion of the equipment.

In this phase of the project it is important to introduce the concept of the sail area of reference (SAR), in which in navigation a sailboat can change in different ways the sail area, relating it according to the force of the wind and the direction of the motion.

To award to a sailboat the desire sailing characteristics, to make it for strong or light wind, open-ocean or lake, it is important to relate the characteristic of the hull with the sail plan: the sail area of reference is important for the base of the study.

For the sloop equipment, which is also the one adopted, it is easy to get the sail area of reference that is made up of the area of two triangles , whose area is expressed by the equation 3.3, and its main parts are shown in Figure 3.5.

$$SAR = \frac{(P * E) + (I * J)}{2} \tag{3.3}$$

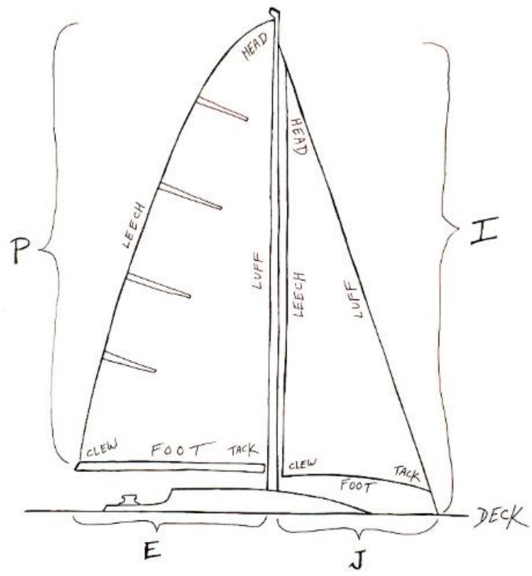


Figure 3.5: Definition of the SAR

In navigation two different situations can be seen that may not occur completely but can coexist simultaneously in variable proportions. In the ride at low speed the phenomena caused by friction are largely dominant compared to the one caused by the wave generation. On the contrary, at speed proximal to the critical speed, the length of the water line and the displacement of the sailboat are more relevant. As a consequence, two ways exist to determinate the sail area of reference, for which it is possible to know if a sailboat will be favorite for light wind or strong wind speed.

In the navigation at low speed, the driving force is proportional to the sail area and the resistance is proportioned to the wet surface of the sailboat. Just comparing these two results is a good way to estimate the SAR. Instead, near the critical speed, the factors that influence this choice are different. The most representative factor of this situation is the ratio $SAR/\Delta^{2/3}$.

3.3 Sail plan

Decided the sail area of reference, and chosen the type of equipment, it occurs now to define the entire sail plan: the group of sails that the boat will use according to the force of the wind and its direction [23]. To make this decision it is important to consider also the characteristic of the sailboat as its stability, shape, position of appendix.

The first thing to do is to fix the position and the height of the mast, to identify the triangle of the bow and the stern. Usually, the sail covers integrally the triangle of the bow, while the triangle of the stern, because of the need of the boom not to touch the back-stay, limits its length and so the measure of the base of the main sail E. It is also important to notice that, as soon as the dimensions of the sailboat allow it, it is important to locate the boom at height so that a standing man will not be reached by the translation of the boom. The images reported in this chapter are taken from internet.

The number of sails that a sailboat will use is straightly related to its conditions of application. The sails can be divided into three main categories:

- Sails hoist on stays;
- Sails hoist on masts;
- Sails with free hoist.

In the first category all the sails like jib or genoa are located; on mast l the mainsail and all sails of storm are set; finally, all the sails like spinnaker or jennaker are considered as free hoist.

An important decision is the choice of the elongation ratio of the sails (I/J and P/E), which in turn influence the height of the mast and the length of the hull. The aerodynamic of the sail has shown that for upwind navigation a larger elongation ratio is an important factor to rise the wind, while for wind hitting from the stern a low elongation ratio is to prefer.

3.3.1 Sketch of the bow sail

The number of the jib that a sailboat may have changes in a very large way. The series of jib starts from the one that has the bigger area and ends with the smaller one. Between these edges the sails are chosen according to the force of the wind, according to keep the driving force constant. Since the force of the wind is proportional to the square of its speed, this means that the area of a sail has to be reduced with a quadratic progression.

The dimensions of all the jibs can be related to each other with the dimension of the biggest genoa, all the characteristics of the bow sails are in Table 3.1. In a practical form, the only dimension that has to be decided to sketch the genoa 1 is its perpendicular LPG, that is expressed as % of J; a good value can be 150-160%. On the forestay, the luff of the genoa has to be as longer as possible, keeping in mind that a certain length is needed on the fore stay to clip the sail. The tack of all the sails will remain the same.

Table 3.1: Characteristics of the bow sails

Sail	Apparent wind speed V_A *(m/s)*	LPG in % of J	LUFF in % of forestay
Genoa 1	5-11	150-160	100
Genoa 2	10-15	130-145	100
Genoa 3	13-18	110-120	95
Jib 1	11-20	90-105	80-90
Jib 2	>20	85	70-80
Storm Jib	>25	70	60

The genoa 1 in navigation is used for light wind, with the increasing of the force of the wind the change of the sail is necessary. The aim of the changes is to keep the driving force constant with the increasing of the force of the wind, reducing the sail area. Therefore, if kept of a constant driving force is required, it is important to have a large number of sails and change it rapidly. On the contrary, if a sailboat is not provided with a large number of jibs, changing from one sail to another will create a notable difference of the driving force on the hull. For the case of study, according to the type of sailboat considered, it is chosen to have two jibs: a genoa 3 and a jib 1.

3.3.2 Sketch of the mainsail

The mainsail is the most important sail for a sailboat because it is the only one that stays always hoisted, while the others are changed; Figure 3.6 presents its main characteristics. It has seen that to ensure the mobility of the boom, the mainsail does not occupy all the space of the stern triangle. To compensate this fact, usually the leech has an elongated shape, and some battens will keep the sail unfurled. Normally for the mainsail are considered two or three referring, each of them leaves out about the 20% of the area, so matters a strip of sails height about 10-15% of P.

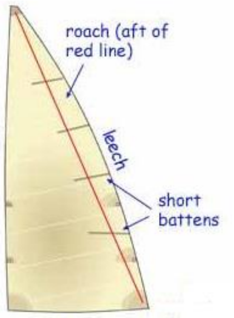


Figure 3.6: Sketch of the mainsail

3.3.3 Sail with free hoist: Spinnaker

The spinnaker is the most largely used sail with free hoist: in fact the study of the aerodynamic resistance shows that the biggest coefficient value of resistance is obtained with a hollow sphere hit by an air flow. This typical configuration is seen in Figure 3.7.

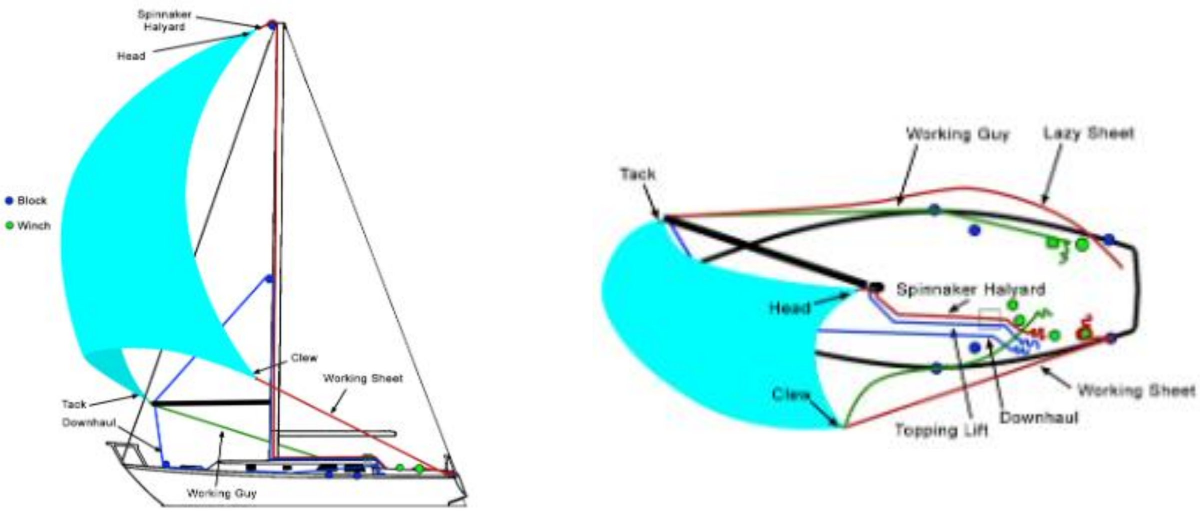


Figure 3.7: Sketch of the spinnaker sail

3.4 Scantling of the equipment

Now it occurs to dimension all the equipment, so give to all the components the right dimension to be able to resist to the force that may occur during navigation: this force may be caused by the force of the wind but also by the wave undulation.

The aerodynamic force is seen as a constant force, or at least weakly variable in a range with a medium value. On the contrary, the wave undulation submits the sailboat to sharp acceleration that may produce on the equipment the outbreak of inertia forces.

It looks reasonable to set the calculations at the baseline of dynamic forces, like the inertia's one, if these were not too difficult to determinate. It is so inevitable to set the calculation basing on the aerodynamic forces, and then take into account the possibility of overload with reasonable safety factors.

Both approaches are wrong, and the problem has to be set in a different way.

In fact, with constant wind or gust, the equipment must never fail, even if the sailboat will be tilt to 90°, thing that happens when the heling moment exceeds the righting moment.

Therefore, the maximum heeling moment is nothing more than the maximum righting moment: this means that the mechanical resistance of the equipment does not have to be based on the force of the wind but has to be studied starting on the stability of the sailboat.

Naturally the condition where the sailboat is heeled by 90° is not normal and represents a condition not really likely. Traditionally it is used to study, as base for the calculation, the righting moment at 30° $RM_{(30)}$, its value is usually near $RM_{(MAX)}$. For the necessity to be able to support even bigger value, safety factors are used that ensure the capability to support also the inertia forces. The images reported in this chapter are taken from internet.

3.4.1 Overview of the rig components

Mast

The mast of a sailing vessel is a tall spar, or arrangement of spars, erected more or less vertically (usually banded backward) on the center-line of the sailboat, its aim is to care the sails. There are a lot of configurations of masts and equipment, the one taken into account for the case of study (that is also the most common) is the sloop configuration with 3 spreaders, one forestay and backstay.

Spreaders

The main aim of the spreaders is to avoid too long unsupported spans of mast that may induce buckling phenomena. A spreader is a spar used to deflect the shrouds and better support the mast by increasing the angle of attack between the shrouds and the mast. Spreaders are mainly loaded in pure compression transmitted by the shroud tension.

Shrouds and stays

For mechanical reasons, the mast has to be sustained with shrouds and stays. The shrouds oppose the transversal movement, instead the stay contrasts just the movement of the head of the mast in longitudinal direction. Shrouds and stays have different aims: the first keeps the mast in transversal position passing to the hull the moments generated by the sails; the stays instead are subjected mostly from the forces generated by the tension of the fore sail, but also from the driving force generated during navigation.

Shrouds can be continuous or discontinuous; the continuous solution consists of full-length shrouds, with constant section, from the mast attachment point down to the chain plates. The discontinuous solution consists in separate spans from two sets of spreaders. In the case of study, discontinuous solution is considered considering different diameters in order to reduce the weight. The shrouds are connected to the hull by chainplates and the stays are connected to reinforced hull points in correspondence of the bow (forestay) and of the stern (backstay).

Regarding mechanical requirements, diagonal shrouds shall generally have a minimum angle to the mast centerline of 9°. If spreaders are swept, they shall be swept evenly, so that all shrouds are in plane on either side, when the rig is unstressed. Spreader sweep angles between 5° and 9° are not advisable, a good angle of sweep has to be found between 10° and 20°. All the components mentioned before are also represented in Figure 3.8.

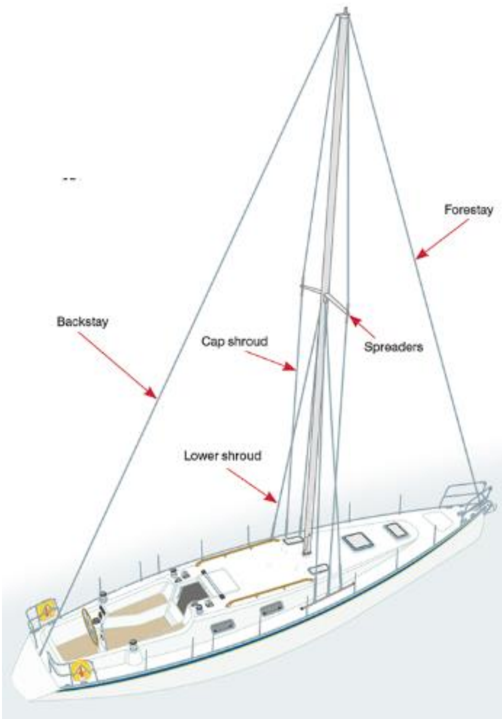


Figure 3.8: Overview of rig components

Boom and vang

The boom is a pole, along the foot of the mainsail, the main aim of it is to keep the base of the main sail flatter and also control the angle of attack with the wind when the sail has to be away from the centerline of the boat. The vang is strictly related with the boom, and it is used to exert downward force on the boom, also control the shape of the sail, in its higher part. The two components are shown in Figure 3.9.

Figure 3.9: Boom and vang configuration

3.5 Scantling rules

The calculations of the rig scantling follow the guideline of Germanischer Lloyd: “Guideline for Design and Construct of Large Modern Yacht Rigs”. As mentioned before, the study of the rig has to perform base on the stability of the sailboat and can be divided in the determination of rig loads (on standing and running rig) and the dimensioning of the rig and all its components. All the images reported in this chapter are taken from [1].

3.5.1 Loading cases

The ordinary sail conditions taken into account, from the upwind to the downwind, each one from light wind to moderate and strong are:

- Full mainsail coupled with the jib1;
- Spinnaker only;
- Full main only;
- Jib1 only.

As mentioned before, the transverse forces on the sails are determined from righting moment of the sailboat [1]. According to this guideline, each sail's contribution to the resultant heeling moment and is assumed to be proportional to the sail’s area and the distance of its center of effort above the underwater body's center of lateral resistance, the position of each barycenter is shown in Figure 3.10.

The value for all following evaluations is the static righting moment (RM) of the yacht at full displacement with a heel angle corresponding to SWA. The "Safe Working Angle (SWA)" represents the heeling angle of 30°.

The sum of these heeling moments is set equal to the vessel’s righting moment under the conditions and specific sail configurations.

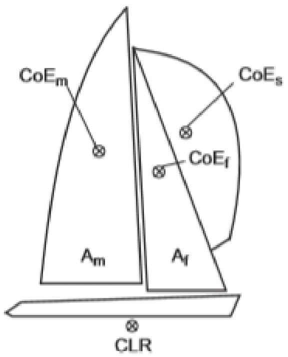


Figure 3.10: Barycenter of each sail and hull

All the formulations presented here are related just to monohull sailboats with one mast, like the case of study.

Transverse force from mainsail:

$$F_{tm} = \frac{RM_{design}}{\overline{CoE_mCLR} + \frac{A_F * SFC_f}{A_m * SFC_m} * \overline{CoE_fCLR}} \; [N] \tag{3.4}$$

Transverse force from foresail:

$$F_{tf} = \frac{A_F * SFC_f}{A_m * SFC_m} * F_{tm} \; [N] \tag{3.5}$$

Transverse force from spinnaker when "broaching".

$$F_{ts} = \frac{RM_{design}}{\overline{CoE_sCLR}} \; [N] \tag{3.6}$$

where all the components here exposed are:

RM_{design} = righting moment [Nm]

$CoE_{m/f/s}$ = centre of effort of respective sail

CoE_m = 0.39 P above gooseneck [m]

CoE_f = 0.39 I above foot [m]

CoE_s = 0.59 I above deck [m]

CLR = The centre of lateral resistance of underwater body [m]

A_m = main sail area [m^2]

A_f = fore sail area [m^2]

P = main sail hoist [m]

E = foot of main sail [m]

I = height of fore triangle [m]

$SFC_f =$ side force coefficient fore sail $= 1.1$

$SFC_m =$ side force coefficient main sail $= 0.9$

After the transversal force associated to each sail has been calculated, it is necessary to check how the force of the wind acting on the sails is transferred to the mast and the rig.

Distribution of transverse sail forces of the mainsail

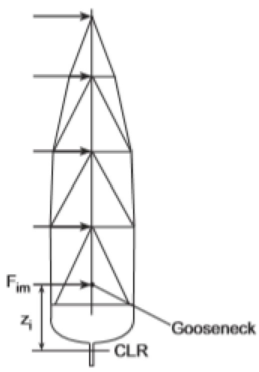


Figure 3.11: Distribution of the transverse sail force of the mainsail

A set of point loads is to be calculated from F_{tm} acting on the mast. The point load distribution shall be appropriate for the specified sail configuration and has to reproduce the equilibrium of moments.

$$F_{im} = c_{im} * F_{tm} \; [N] \tag{3.7}$$

where:

F_{tm} = transverse force main sail $[N]$

c_{im} = distribution factor with:

$$\sum_{i=1}^{n} c_{im} = 1$$

z_i = according to Figure 3.11

The load points considered where the mainsail is to transmit the force of the wind on the mast are: main headboard, spreaders 1,2,3 and the gooseneck. The clew is not taken into account because the transverse force of the mainsail is passing directly through the boom.

Distribution of transverse sail forces of the foresail

The same considerations are computed for the fore sail (jib1). The transversal force used is the one related with the foresail: F_{if}.

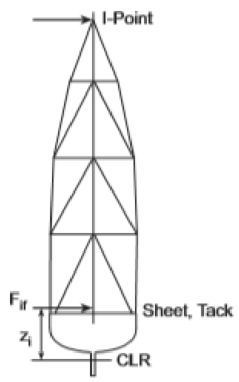


Figure 3.12: Distribution of the transverse sail force of the foresail

Different are the load points on the rig, the transversal force is transmitted to the mast just from the head of the sail instead the other points of the sail (tack and clew) directly transmit the force of the sail to the hull, so it will not be taken into account.

$$F_{if} = c_{if} * F_{tf} \; [N] \tag{3.8}$$

where:

F_{tf} = transverse force fore sail

c_{if} = distribution factor with:

$\sum_{i=1}^{n} c_{if} = 1$

z_i = according to Figure 3.12.

Distribution of transverse sail forces of the spinnaker

The same considerations are computed for the spinnaker. The transversal force used is the one related with the foresail: F_{is}.

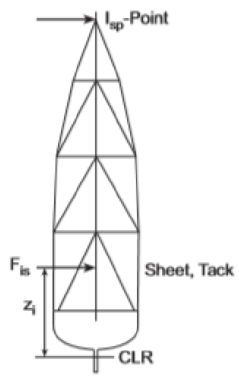


Figure 3.13: Distribution of the sail force of the spinnaker

Different are the load points on the rig, the transversal force is transmitted to the mast just from the head of the sail instead the other points of the sail (tack and clew) directly transmit the force of the sail to the hull, so it will not be taken into account.

$$F_{is} = c_{is} * F_{ts} \, [N] \tag{3.9}$$

where:

$\mathrm{F_{ts}} = \text{transverse force spinnaker}$

$\mathrm{c_{is}} = \text{distribution factor with:}$

$\sum_{i=1}^{n} c_{is} = 1$

$\mathrm{z_i} = \text{according to } Figure\ 3.13.$

Determination of working loads of running rigging

The following approaches are to be seen as a general estimation of an initial calculation value.

The working load of a halyard is generally generated by the forces in a sail. Its magnitude depends on the amount of sag of the leech including a preload due to hoisting. Determination of the halyard load is to be based on design righting moment and the following sail configuration: Full main and 100 % foresail.

- Mainsail halyards:

$$F_{ml} = manisail\ leech\ load = \frac{F_{ml}}{8 * s} * f_r \, [N] \tag{3.10}$$

$$f_r = roach\ factor = \frac{A_m}{0.5 * P * E} \, [N] \tag{3.11}$$

$\mathrm{s} = \text{sag fraction}$

$= 0.065, (6.5\% \text{ of leech lenght}) \text{for all categories}$

- Foresails (genoa, jib, staysail, etc.) halyards:

$$F_{fhy} = 1.02 * \frac{F_{tf}}{8 * s} \, [N] \tag{3.12}$$

$\mathrm{s} = \text{sag fraction}$

$= 0.045, (4.5\% \text{ of leech lenght}) \text{for all categories}$

Determination of working loads of standing rigging

This guideline examines standing rigging sizes by calculating tensile forces and correlate them with the reserve factors, as shown later. The tensile forces determined this way are also called maximum working loads (MWL) under the conditions of these Guidelines.

- Headstays:

The working load is the resultant axial force due to sag of a sail-carrying head stay. The sag is the maximum transverse deflection of a line under a lateral uniform load between its ends, it is clearly visible in Figure 3.15.

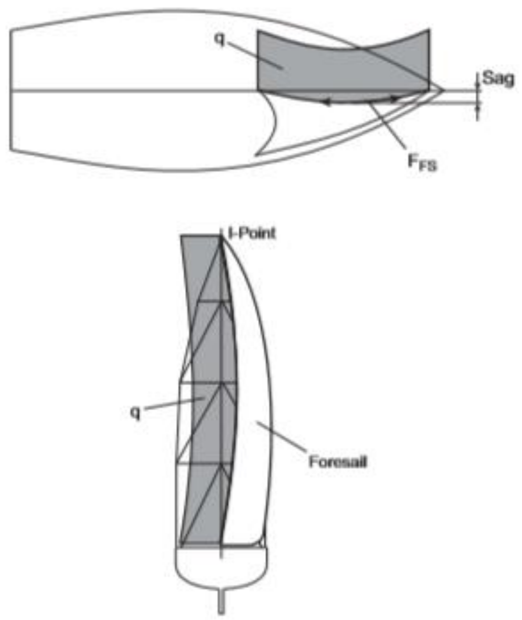


Figure 3.14: Sag of the bow sail

The values specified below are relevant for the load case of a full main combined with a jib of 100 % forestay-triangle area. The lateral load "q" is a uniform load equivalent to the force F_{ts}.

Head stay working load:

$$F_{hs} = \frac{q * l_0}{8 * s} \; [N] \tag{3.13}$$

$$q = \frac{F_{ts}}{l_0} \; [N/m] \tag{3.14}$$

l_0 = stay lenght [m]

s = the magnitude of sag sas a fraction of th stay lenght is not to be taken more than to Table 3.2.

Table 3.2: Magnitude of sag

	sag			
	Cat. IV	Cat. III	Cat. II	Cat. I
Primary headstay	0.7%	1.0%	1.5%	2.0%
Secondary headstay	1.5%	2.5%	3.0%	5.0%

The sailboat case of study is considered as a category three.

- Backstay

For masthead rigs, backstay design load is obtained by opposing the forestay design load under equilibrium of moments of the mast base. In case of swept spreaders, a contribution of cap shrouds may be considered.

3.5.2 Distribution of the forces on the rig

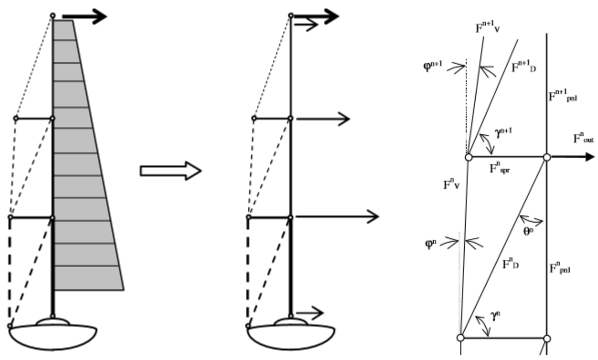


Figure 3.15: Distribution of the forces on the rig

As it was calculated in the previous chapter, the forces acting on the sails are redistributed first from the mast to the hull passing through the shrouds. The sketch of the idea is explained in Figure 3.16. The point of load where this force is transmitted is for the jib 1 the headboard of the mast, while for the mainsail are the headboard, the three spreaders and the gooseneck. A good representation is given in the image here proposed.

After having obtained the five forces acting on the mast, the force of each shroud is calculated analytically knowing a priori the configuration of the shrouds, the spreaders and the length of each panel of the mast. The configuration of the rig is set down to have a sweep of the spreaders of 15°, a constant division between the four panels of the mast of 20.70 meters. The spreaders are divided into four diagonals (d) and three verticals (v).

3.5.3 Dimensioning of the shroud

The dimensioning of the shrouds is done according to the following reserve factors (RF). They are related to the ultimate break load specified valid for Nitronic 50 Rod rigging.

Regarding the type of rig and its components, the guideline suggests to use:

- Transverse rigging: $RF \geq 2.5$ on working load determined before;
- Fore and aft rigging: $RF \geq 2.0$ on design load.

3.5.4 Global stability and stiffness of mast

For the mast design, the method adopted is present in reference Principle of Yacht Design.

In this method, the type of mast is chosen between top or factionary mast, then the number of spreaders that make up the mast is chosen. It is worth mentioning that the spreaders help to resist the moments generated by the sails.

The mast has to contrast two different stresses that are caused by the tension of the shrouds and stay that induce a compression in the mast, and in order not to bend or break, it has to have a sufficient stiffness and enough transversal and longitudinal inertia.

Regarding the transversal inertia I_x, the formulation is given and is common to all rig types, the only differences in the results are caused by the possible different panel length. Another factor that may change between the different rigs is the panel factor k_1 and the “foot factor” k_3.

PT is the design load calculated using again the righting moment of the yacht at 30°, it want to consider the compression of the mast tube due to the pretension of the rig and the moment generated by the sail’s force. The value is multiplied by 1.5 to handle dynamics factors.

The equations used for the required transverse moment of inertia, are presented as follow:

$$I_x = k_1 * m * PT * l^2 \; [mm^4] \tag{3.15}$$

$$PT = 1.5 * \frac{RM}{b} \; [N] \tag{3.16}$$

where:

$m = 1$ for aluminum;

$l =$ actual panel length;

$k_3 = 1.35$ for deck stepped masts;

k_1: values reported in *Table 3. 3*.

Table 3.3: Values of k_1

n. of the panel (-)	Value of k_1 (-)
$Panel_0$	3.915
$Panel_1$	3.950
$Panel_2$	3.950
$Panel_3$	3.950

The equation used for the required longitudinal moment of inertia, is presented as follows:

$$I_y = k_2 * k_3 * m * PT * h^2 \ [mm^4] \tag{3.17}$$

where:

- $k_2 = 0.85$: staying factor;
- h = height above deck to the highest sail carrying forestay.

3.6 Pressure and flow around the sails

A sail is a wing that for its construction made of fabric is virtually assumed to have no thickness. But it has to work in a disturbed flow caused by the mast for the mainsail and by the forestay for the aft sail.

All the images reported in this chapter are taken from [2].

3.6.1 Flow around the sail

As it was said, the sail for its construction has to work hoisted to a mast or a forestay and flow disturbances are generated. In Figure 3.17 how the flow around the mainsail acts is analyzed if the interference of the mast is not considered. It can be seen that the negative pressure, on the upward, on the suction side is much larger than the positive one on the pressure side. The theory of the wing explains that the difference of pressure between the sides gives the force and this force will be much larger from the suction side [31].

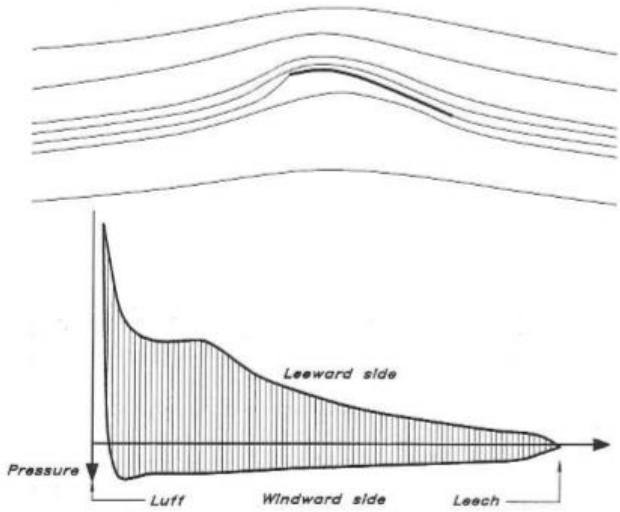


Figure 3.16: Flow and pressure distribution for a sail

In the next example, from Figure 3.17 to Figure 3.19, the mainsail and the jib are presented, working together. As it can be noticed, the flow around the two cases is completely different. Approaching the sails, the thick lines bend much further apart than the thin ones, this means that the air approaches the mainsail at a smaller angle than in the single sail case. This situation will unload the mainsail (reducing the pressure gap), while the jib will face a major load. This situation is reflected in the pressure plot.

Figure 3.17: Flow around jib and mainsail

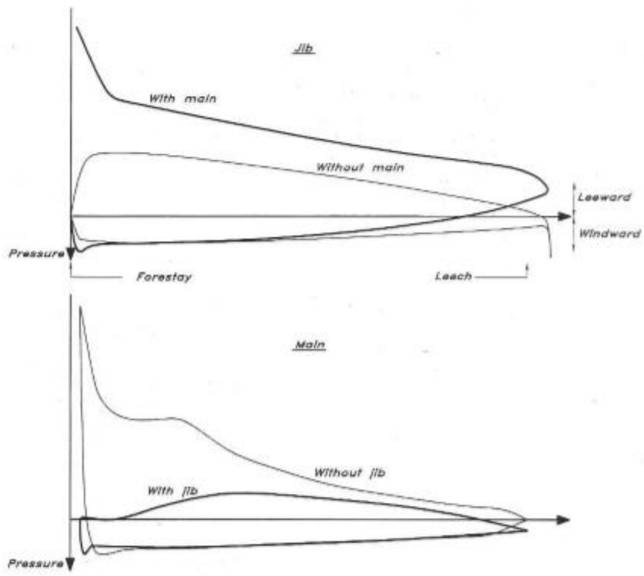


Figure 3.18: Pressure distribution for mainsail and jib

How it can be noticed, this reflects that most of the suction over the forward half of the mainsail has disappeared and the total force, represented by the area between the pressure curves on the two sides, has dropped considerably. On the other hand, the suction on the leeward side of the jib has increased from the leading to the trailing edge and forces are much larger. This example is based on an idealized model of the flow, where viscosity is neglected.

3.6.2 Mast interference

All sailboats need a mast to hoist the sails, but it can cause bad interference with the sail if it is not well designed.

As it is shown in Figure 3.20 the flow around the mast and the mainsail is not attached to all the length of the sail and three zones of separation can always be found. Two immediately behind the mast (windward and leeward), while the third zone is found in the aft part of the sail leeward side. The separation just behind the mast can be minimized by a good design of the mast section. The third separation part depends to some extent on the forward one, since a massive separation forward causes a thick boundary layer to develop in the attached part of the flow. By proper sheeting and a good mast design this zone can be very small or even eliminated.

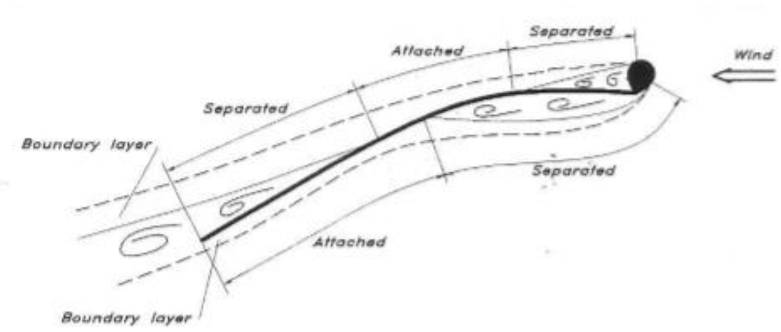


Figure 3.19: Mast interference

There are two main reasons why separation zones have to be avoided. First the pressure distribution is disturbed, and then the pressure differences between the two sides of sail are reduced causing, as it can be imagined, a reduction of lift and driving force. As a second cause, the separation causes an increase of drag. In the case of study, in the design of the mast section, this effect will be taken into consideration trying to minimize as much as possible the section without creating lack of resistance in the mast [24].

3.7 Practical model for sail and rig aerodynamic

The model used for the aerodynamics of sails of the yacht was presented in 1980 by G. Hazen, the original model and the later improvements adopted will be described. In the Hazen's model the lift and viscous drag of each sail are described as function of the apparent wind angle. The coefficients are presented in Table 3.4, for both lift and drag.

The coefficients are given for these apparent wind angles: 27°, 50°, 80°, 100°, 180°, intermediate values are calculated with linear interpolation. The coefficients are given for five sails: main sail, jib, spinnaker, mizzen sail, mizzen stays.

To get the total lift and drag, the area of each sail has to be multiplied by the corresponding coefficient and all sail added. The final coefficient is obtained by dividing by the nominal sail area (sum of main sail and jib area). In the model there is no explicit interaction between the sails, but the blanketing of the main sail by the jib is taken into account.

The induced drag coefficient is proportional to the square of the lift coefficient and inversely to the aspect ratio. In the method, the entire nominal sail plan is considered when computing the aspect ratio, and the induced drag is computed for all sails.

In the model, it is also taken into account the drag of mast and the topsides taking into account the average freeboard times the maximum beam and the mean diameter for the mast.

All the images reported in this chapter are taken from [2].

Table 3.4: Lift and drag coefficient of the G. Hazen model

Sail coefficient, lift					
Angle (°)	Main sail (-)	Jib (-)	Spinnaker (-)	Mizzen (-)	Miz. Stays (-)
27	1.50	1.50	0.00	1.30	0.00
50	1.50	0.50	1.50	1.40	0.75
80	0.95	0.30	1.00	1.00	1.00
100	0.85	0.00	0.85	0.80	0.80
180	0.00	0.00	0.00	0.00	0.00
Sail coefficient, viscous drag					
Angle (°)	Main sail (-)	Jib (-)	Spinnaker (-)	Mizzen (-)	Miz. Stays (-)
27	0.02	0.02	0.00	0.02	0.00
50	0.15	0.25	0.25	0.15	0.10
80	0.80	0.15	0.90	0.75	0.75
100	1.00	0.00	1.20	1.00	1.00
180	0.90	0.00	0.66	0.80	0.00

The barycenter of the sails is taken to be: 39% of the luff length above the boom for main sail, mizzen and mizzen staysail. For jib and spinnaker, it is respectively 39% and 59% of the fore triangle height above the sheer line.

Area: (3.18)

$$main\ sail: A_M = 0.5 * P * E$$

$$fore\ sail: A_J = 0.5 * LPG * \sqrt{I^2 + J^2}$$

$$spinnaker\ sail: A_s = 1.15 * SL * J$$

$$mizzen\ sail: A_s = 0.5 * PY * EY$$

$$mizzen\ staysail\ sail: A_{ys} = 0.5 * YSD * (YSMG + YSF)$$

$$fore\ trinagle: A_F = 0.5 * I * J$$

Centre of effort: (3.19)

$$CE_M = 0.39 * P + BAD$$

$$CE_J = 0.39 * I$$

$$CE_S = 0.59 * I$$

$$CE_Y = 0.39 * PY + BADY$$

$$CE_{YS} = 0.39 * PY + BADY$$

$$Nominal\ area: A_N = A_M + A_J + A_Y \tag{3.20}$$

$$Lift: C_L = \frac{C_{LM} * A_M + C_{LJ} * A_J + C_{LY} * A_Y + C_{LYS} * A_{YS}}{A_N} \tag{3.21}$$

$$Viscous\ drag: C_{DP} = \frac{C_{DPM} * A_M + C_{DPJ} * A_J + C_{DPY} * A_Y + C_{DPYS} * A_{YS}}{A_N} \tag{3.22}$$

$$Induced\ drag: C_{DI} = C_L^2 * (\frac{1}{\pi * AR} + 0.005) \tag{3.23}$$

$$Close\ hauled: AR = \frac{(1.1 * (EHM + FA))^2}{A_N} \tag{3.24}$$

$$Other\ courses: AR = \frac{(1.1 * EHM)^2}{A_N} \tag{3.25}$$

$$Drag\ of\ mast\ and\ topsides: C_{DO} = \frac{1.13 * (BMAX * FA) + (EHM * EMDC)}{A_N} \tag{3.26}$$

$$Total\ drag: C_D = C_{DP} + C_{DI} + C_{DO} \tag{3.27}$$

Standard IOR notation:

P: main sail hoist

E: foot of main sail

I: height of fore triangle

J: base of fore triangle

LPG: perpendicular of longest jib

SL: spinnaker leech

PY: mizzen hoist

EY: foot of mizzen

YSD: mizzen staysail depth

YSMG: mizzen staysail mid-girth

YSF: mizzen staysail foot

BMAX: max beam of yacht

FA: average freeboard

EHM: mast height above sheer

EMDC: average mast diameter

BAD: height of main boom above sheer

BADY: height of mizzen boom above sheer

The sail forces provided by the model are lift and drag components. To be useful for predictions the components parallel to, and at right angles to, the direction of motion are required. Figure 3.21 explains how lift and drag are converted into drive force and side force.

Another geometrical transformation has to be done to obtain forces for heeled condition; no considerations were taken into account before.

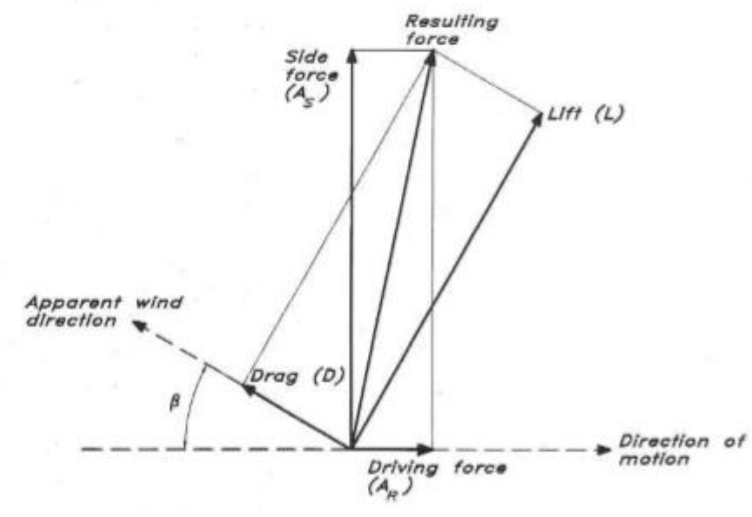


Figure 3.20: Geometrical conversion from lift and drag to drive and side force

This is done separately, instead of modifying all the coefficients, the apparent wind speed and direction are computed in a plane that heels with the yacht. This transformation can be done really easily as shown in Figure 3.22. The component of the apparent velocity along the hull is unchanged by the heel, while the component at right angles there is proportional to the cosine of the heel angle; the leeway of the yacht is neglected.

$$A_S = L * \cos(\beta) + D * \sin(\beta) \tag{3.28}$$

$$A_R = L * \sin(\beta) - D * \cos(\beta) \tag{3.29}$$

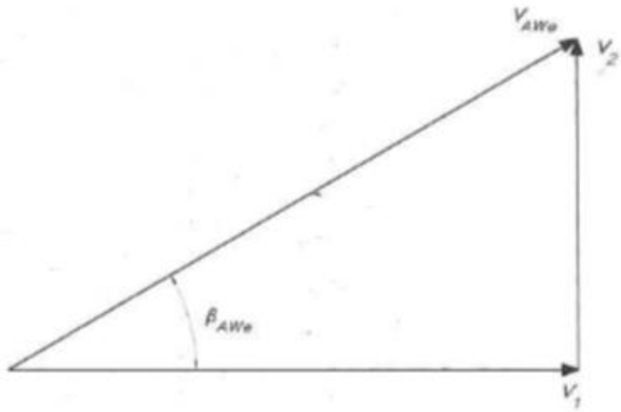


Figure 3.21: Composition of the apparent wind

$$V_1 = V + V_{TW} * \cos(\beta_{TW}) \tag{3.30}$$

$$V_2 \cong V_{TW} * \sin(\beta_{TW}) * \cos(\emptyset) \tag{3.31}$$

$$V_{AWe} = \sqrt{V_1^2 + V_2^2} \tag{3.32}$$

$$\beta_{TWe} = \tan^{-1}\left(\frac{V_1^2}{V_2^2}\right) \tag{3.33}$$

where:

V_{TW}: true win velocity

V_{AWe}: effective apparent wind velocity

β_{TW}: true wind angle

β_{TWe}: effective apparent wind angle

$\emptyset$: heel angle

V_1: apparent wind velocity along direction of motion

V_2: apparent wind velocity at right angles to mast and direction of motion

3.8 Modal analysis

After the quasi-static response and its characteristic are computed, a modal analysis is performed to identify the dynamic characteristics of the mast. The modal analysis is the dynamic study to provide information about the structure's dynamic behavior when the structure is vibrating. This analysis is important for our case because the dynamic responses analysis of the mast subjected to wind force is relevant to its dynamic characteristics.

The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions and is also required if a spectrum analysis is performed. For the complexity of the structure, the analysis is carried out with the software Ansys. The mast structure is studied, finding the first three natural modes in the longitudinal and transversal direction.

To perform the study, no forces have to be applied; just the displacement of shrouds and stays in order to reach the known pretension of the rig. It is not related to the loading at this stage, only to the geometry. Resonance frequencies change due to the shape of the model and the way it is constrained only.

The input value for the analysis can be of two types: as first, it can be input the initial and final frequency the analysis wants to be carried out or as second it can be input the numbers of modes that need to be found.

As the structure is composed by different parts joined together to find the first three natural modes of the mast tube, a large number of modes is input to find: 100. After this second analysis each mode is exanimated and the frequencies that were implying just the mast tube were chosen.

3.9 Wind spectrum

The generation of the wind spectrum is done according to the reference [1], which proposes various types of spectrum idealization. According to the type of study carried on and on reference [21], it is decided to adopt the Kaimal spectrum for the wind representation.

In the reference [1] two main components of the wind speed are found: the stationary component, that is characterized by few changes and a turbulent component that are characterized by high frequencies of changes. It is exactly this component that may induce quick and unpredictable behavior in the structure.

The wind speed can be described as:

$$v(t) = v_s(t) + v_t(t) \tag{3.34}$$

where $v_s(t)$ is the stationary component and $v_t(t)$ is the turbulent one.

The *Kaimal* spectrum used described the turbulent component considering constant the stationary one, equal to the average mean speed of the wind $\bar{v}_m(t)$. This approximation is acceptable if the simulation is done in the temporary scale of a turbulence, so in the time of *10/15* minutes.

The turbulence is studied in a statistic way, whose main quantities are:

L_u that is the turbulence length scale, described as: $L_u = 300 \left(\frac{z}{300}\right)^{0.46+0.074 \ln z_0}$.

where z denotes the height above the ground or the sea water level.

z_0 is the terrain roughness. A vale of 0.0001 is used for open water without waves and $0.0001 - 0.01$ is considering the effect of the waves in open sea. The unit has to be $[m]$.

f is the range of frequency considered $[Hz]$.

σ_u is the distribution of the standard deviation. According to the *normal turbulence model, NTU* is described as: $\sigma_u = I_{Ref} * (0.75 * \overline{v_m} + 5.6)$.

where $I_{Ref} = 0.14$ and $\overline{v_m}$ is the average wind speed.

The *Kaimal* spectrum gives the following expression for the spectral density, considering the reference [1].

$$S_{v_m}(f) = \sigma_u{}^2 \frac{6.868 * {}^{L_u}/_{v_m}}{(1 + 10.32 * f * {}^{L_u}/_{v_m})^{5/3}} \tag{3.35}$$

4. CASE STUDY

4.1 Overview of the yacht

To start the study, a yacht with main dimensions and weight distributions based on an example sailboat in *DELFTShip* software, is chosen. The example is a racing yacht of 50feet, and its hull is shown in Figure 4. 1.

Figure 4.1: DELFTShip model of the simulation

Table 4.1: Main dimensions

Main dimensions	Values	Unit
L_{BP}	15	(m)
B	4.7	(m)
T	2.75	(m)
Δ	10.4	(t)

Table 4.2: Main parts weight

Main parts weight	Values	Unit
hull	3.8	(t)
keel	0.9	(t)
bulb	3.5	(t)
rudder	0.2	(t)
deck	1	(t)
doghouse	1	(t)
Δ	10.4	(t)

Lightly adjustment is made on the shape of the yacht. The consistent part is the definition of the weight of the various section of the yacht, based on similar yacht with same dimensions and aim. The main parts of the yacht hull are: hull, keel, bulb lead, rudder, deck and doghouse. In addition, for each part, the weight is given in Table 4.2 and the dimensions of the yacht are shown in Table 4.1.

After the adjustment done on the hull, the software *DELFTShip* is used to get the hydrostatic characteristics. The main information is presented in Table 4.3 and Table 4.4. The first table presents the position of the center of buoyancy of all the structural part of the hull while the second one shows the position of the center of gravity of the hull.

The hydrostatic calculation gives also information about the volume's properties of the submerged body and the sectional areas in the transversal plane of the hull. All of these results are reported in appendix [A].

Table 4.3: Position of L_{CB} and V_{CB}

Parts	L_{CG} (m)	V_{CG} (m)	T_{CG} (m)
hull	7.065	2.982	0.0
keel	8.130	1.230	0.0
bulb	7.793	0.265	0.0
rudder	0.650	1.932	0.0
deck	5.263	3.869	0.0
doghouse	8.209	4.515	0.0
sum	7.215	2.129	0.0

Table 4.4: Position of LCG and VCG

Parts	LCB (m)	VCB (m)	TCB (m)
hull	6.982	2.690	0.0

4.2 Stability (Archimedes)

To compute the design and scantling of the rig, everything is based on the righting moment of the hull at 30° of heeling. Each sail's contribution to the resultant heeling moment is assumed to be proportional to the sail's area and the distance of its center of effort above the underwater body's center of lateral resistance. The sum of these heeling moments is set equal to the vessel's righting moment.

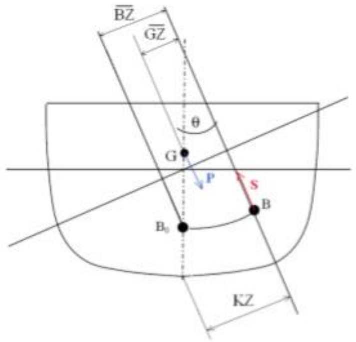


Figure 4.2: Sketch of the stability forces acting [22]

To calculate the righting moment of the yacht, the software *Archimedes* is used. Its main scope is to define the displacement of the center of buoyancy caused by transversal inclinations compared to its position of the uninclined yacht. For each angle considered in the software, from 0° to 180°, and for a fix displacement is given the value of the arm of buoyancy $\overline{KZ}$. The main sketch of the stability is proposed in Figure 4.2, where $\overline{\mathrm{KZ}}$ represents the projection on the transversal plane of the arm of the vector of the buoyancy compared to the point of intersection between the base line and the transverse plane that contains the isocarene center of the uninclined hull.

The value $\overline{\mathrm{KZ}}$ is an important parameter because it is related to capacity of the hull to oppose by any tilting force. In the computation of the righting moment of the yacht is more important the knowledge of the value $\overline{GZ}$ that is given by a simple geometrical transformation: $\overline{\mathrm{GZ}} = \overline{\mathrm{KZ}} - \mathrm{VCG} * \sin\vartheta$. The segment $\overline{\mathrm{GZ}}$ is presenting the harm of moment between buoy and weight force and with the knowledge of $\overline{\mathrm{GZ}}$, it is possible to draw the curve of the righting moment: $\mathrm{RM}_{(\theta)} = \overline{\mathrm{GZ}} * \Delta$ as shown in Figure 4.3.

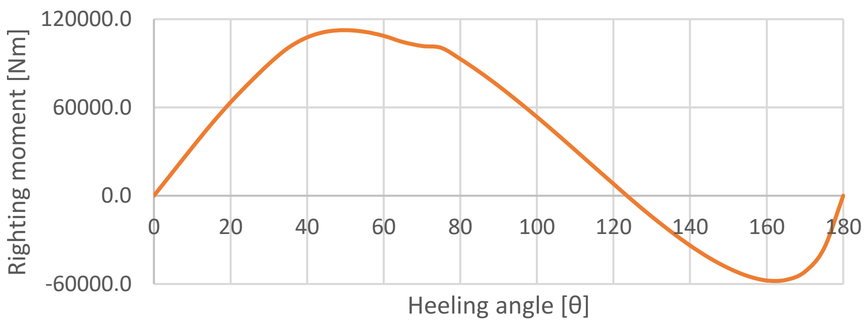


Figure 4.3: Graph of the stability of the sailboat

4.3 Determination of the sail area of reference SAR

In the first part of the project, it is relevant to get an approximate value of the sail area of reference (SAR). With the knowledge of the SAR it is possible to sketch the design of the mast.

In the computation of the SAR are considered: the type of hull, that requires a high-performance sailing and the possibility of the yacht to sail near and over the critical speed. The most representative factor of this situation is the ratio $SAR/\Delta^{2/3}$ [3]. It is used as reference in the graph shown in Figure 4.4, which gives an approximately idea of a value of the sailing area of reference as function of the water line length.

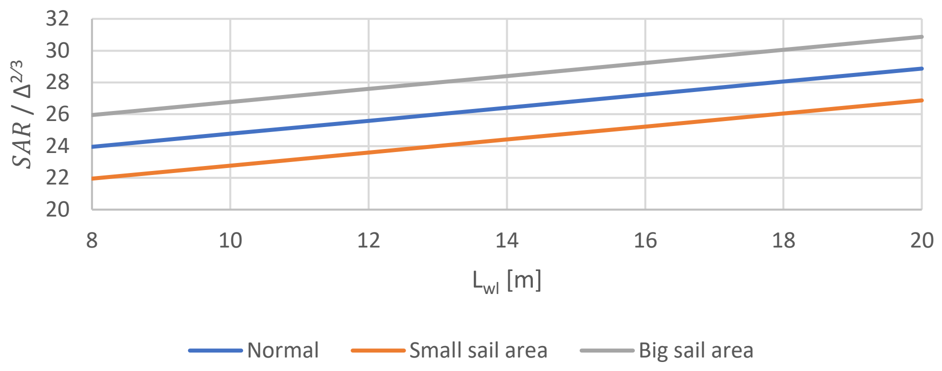


Figure 4.4: SAR determination

Extreme values of displacement of the yacht and the length of the water line are calculated and shown in Table 4.5, since they are input parameters.

Table 4.5: SAR determination

Sail area	$L_{WL\ real}$ (m)	$SAR / \Delta^{2/3}$	SAR (m^2)
Small sail area	14.298	24.53218	116.885
Normal sail area	14.298	26.53218	126.414
Big sail area	14.298	28.53218	135.943

In this part, it is important to compare and check the results with similar sailboats since the value of SAR can variate consistently.

4.3.1 Drawing of the sail plan and mast configuration

After having an idea of the value of the SAR, it is important to choose the type of equipment and define the entire sail plan. For the type of equipment, the yacht is designed to be sloop. The position of the mast and its height must be decided, in order to identify the triangle of bow and stern. The main parameter used for this computation is the elongation of the sail and naturally the physical space on the deck of the yacht.

As the study considers only three sails: mainsail, jib and spinnaker, only a Jib 1 is considered for the triangle of bow. It will almost close the triangle without overlapping with the main sail. The elongation ratio of this sail is considered as 3, which is the standard value for this sail. Regarding the main sail, the only main consideration done was to locate the height of the boom to avoid that a standing man would be reached by the translation of the boom and its length touches the back-stay.

With all these considerations, the mast is 20.7 meters of height, the boom is 5.5 meters length and is located 1.3 meters up the mast's step. With a final value of SAR of 127.7 meters square. In Table 4.6 all the final values of the sail plan configuration are listed, where P is height of the mainsail, E means the length of the base of the mainsail, I denotes height of the fore triangle, and J is base of the fore triangle.

Table 4.6: Mast and sail plan configuration

SAR	127.7	(m^2)	Sail area of reference
P	19.7	(m)	Height of the mainsail
E	5.5	(m)	Length of mainsail base
P/E	3.6	(-)	-
I	20.7	(m)	Height of the fore triangle
J	7	(m)	Length of fore triangle base
I/J	2.96	(-)	-

With a height of 20.7 meters, the mast is divided into four panels with the same length of 5.175 meters, as listed in Table 4.7. This is done to avoid possible buckling in induced by too long distance between the spreaders and for similitudes between other yachts, which are between four and three panels. Each spreader has an angle of attack of 20°. The dimension of all the spreaders, panels and the length of all the shrouds are shown in Table 4.8-4.9.

All the measures are performed in the software Rhino 3D manually by importing the *DELFTShip* model. The model is shown in Figure 4.5 where all the main lines used to design properly the rig system are plotted. The software is useful also to get the right position of the center of gravity of the two sails.

Table 4.7: Mast panel's definition

Part	Length (m)	Height from foot mast to end panel (m)
$Pannel_0$	5.175	5.175
$Pannel_1$	5.175	10.350
$Pannel_2$	5.175	15.525
$Pannel_3$	5.175	20.700

Table 4.8: Spreaders definition

	Length of transversal projection (m)	Length of spreader (m)	Height from foot mast (m)
Base	1.90	2.02	-0.716
Spreader $_1$	1.90	2.02	5.175
Spreader $_2$	1.90	2.02	10.350
Spreader $_3$	1.60	1.70	15.525
Top	0.00	0.00	20.700

Table 4.9: Shrouds definition

Shroud ID	Length (m)	Shroud ID angle	Angle (°)
V_n	5.891	β_n	20.475
D_n	6.228	γ_n	0.000
V_{n+1}	5.175	β_{n+1}	23.599
D_{n+1}	5.556	γ_{n+1}	0.000
V_{n+2}	5.185	β_{n+2}	23.599
D_{n+2}	5.556	γ_{n+2}	3.539
D_{n+3}	5.448	β_{n+3}	19.563

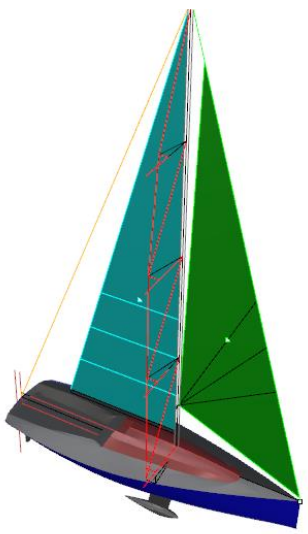


Figure 4.5: 3D model of Rhino

4.4 Mechanical proportion of the equipment

4.4.1 Transverse sail force

Transverse forces are determined from righting moment as mentioned before. Each sail's contribution to the resultant heeling moment is assumed to be proportional to the sail's area and the distance of its center of effort above the underwater body's center of lateral resistance. As specified in the guideline, heeling moment considered for the calculation of the transverse sail forces is at "Safe Working Angle (SWA)", which represents a heeling angle of 30°.

Table 4.9: Main data for the transversal force

Parameters	Values	Unit
$RM_{(\text{Heeling angle } 30°)}$	89536.7	(Nm)
$CoE_{m\,(\text{Main sail})}$	12.2	(m)
$CoE_{f\,(\text{Jib 1})}$	11.4	(m)
$CoE_{s\,(\text{Spinnaker})}$	16.2	(m)
CLR	1.9	(m)
$A_{m\,(\text{Main sail})}$	54.2	(m^2)
$A_{f\,(\text{Jib})}$	62.4	(m^2)
P	19.7	(m)
E	5.5	(m)
I	20.7	(m)
J	7.0	(m)
SFC_m	0.9	(-)
SFC_f	1.1	(-)

First case: mainsail coupled with jib

Table 4.10: First case: mainsail and jib

Transverse force from mainsail coupled with Jib		
F_{tm}	3791.3	(N)
M_{tm}	39077.3	(Nm)
Transverse force from jib coupled with the main sail		
F_{tf}	5335.7	(N)
M_{tf}	50459.4	(Nm)

Table 4.11: Distribution of the sail forces first case

Distribution of transverse sail forces of the main sail				
Application of the force	Distribution factor c_{im} (-)	F_{im} (N)	z_i (m)	M_{tm} (Nm)
clew (not on rig)	0.16	608.8	3.75	2283.0
tack	0.09	324.1	3.75	1215.5
spreader 1	0.33	1252.2	8.03	10048.6
spreader 2	0.24	915.3	13.20	12082.1
spreader 3	0.14	545.6	18.38	10025.6
main head	0.04	145.3	23.55	3422.5
	1.00	3791.3	2.85	39077.3
Distribution of transverse sail forces of the jib				
Application of the force	Distribution factor c_{if} (-)	F_{if} (N)	z_i (m)	M_{tf} (Nm)
tack (not on rig)	0.40	2126.4	2.73	5804.9
clew (not on rig)	0.29	1573.0	3.89	6118.9
main head	0.31	1636.3	23.55	38535.6
	1.00	5335.7	2.85	50459.4

Second case: Spinnaker

Table 4.12: Transverse force from spinnaker when "broaching" for the second case

F_{ts}	6256.9	(N)
M_{ts}	89536.7	(Nm)

Table 4.13: Distribution of transverse sail forces of the spinnaker for the second case

Application of the force	Distribution factor c_{if} (-)	F_{is} (N)	z_i (m)	M_{ts} (Nm)
tack (not on rig)	0.23	1230.9	2.73	3360.5
clew (not on rig)	0.10	533.6	3.89	2075.6
main head	0.67	3571.2	23.55	84100.7
	1.00	5335.7	2.85	89536.7

Third case: mainsail only

Table 4.14: Transverse force from mainsail only

F_{tm}	8687.0	(N)
M_{tm}	89536.7	(Nm)

Table 4.15: Distribution of transverse sail forces of the main sail only

Application of the force	Distribution factor c_{im} (-)	F_{im} (N)	z_i (m)	M_{tm} (Nm)
clew (not on rig)	0.28	2460.2	3.75	9225.6
tack (not on rig)	0.08	671.2	3.75	2517.1
spreader 1	0.18	1530.7	8.03	12283.7
spreader 2	0.23	1998.1	13.20	26374.6
spreader 3	0.19	1661.1	18.38	30522.2
main head	0.04	365.7	23.55	8613.4
	1.00	8687.0	2.85	89536.7

Fourth case: jib only

Table 4.16: Transverse force from jib 1 only

F_{tm}	9467.8	(N)
M_{tm}	89536.7	(Nm)

Table 4.17: Distribution of the sail forces fourth case

Application of the force	Distribution factor c_{if} (-)	$F_{if\,(Jib\,1)}$ (N)	z_i (m)	M_{tf} (Nm)
tack (not on rig)	0.40	3773.1	2.73	10300.5
clew (not on rig)	0.29	2791.2	3.89	10857.6
main head	0.31	2903.6	23.55	68378.7
	1.00	9467.8	2.85	89536.7

The mechanical proportional of the equipment is calculated with four different combinations of sails: mainsail coupled with jib, only the mainsail, only the jib and the spinnaker. The main data used to get the transverse forces and its distribution on the mast for the four different cases are presented in Table 4.10-4.18.

4.4.2 Determination of working loads on standing rigging

Importantly, the objective of the section is to have an idea of the tension of the head stay to have a good value of sag for the jib. The sag is the maximum transverse deflection of a line under a lateral uniform load between its ends that in this case is between the jib head and its clew. The magnitude of sag is considered to be 1%. With this value, the head stay working load has to be at least of *66695.9 N* for the condition of main sail coupled with the jib. The minimum tension required will be reached with the pretension of the rig. The backstay load is obtained by opposing the forestay design load under equilibrium of moments about the mast base.

First case: mainsail coupled with jib

Table 4.18: First case: mainsail and jib

Item ID	Shroud tension (N)	RF reserve factor GL >= 2.5 (-)	Dimensioning of standing rigging GL (N)
D_{n+3}	5321.0	2.5	13302.5
V_{n+2}	5023.4	2.5	12558.5
D_{n+2}	5038.6	2.5	12596.6
V_{n+1}	9650.3	2.5	24125.7
D_{n+1}	8099.6	2.5	20248.9
V_n	17072.4	2.5	42681.1
D_n	12849.3	2.5	32123.2

Second case: Spinnaker

Table 4.19: Second case: spinnaker

Item ID	Shroud tension (N)	RF reserve factor GL >= 2.5 (-)	Dimensioning of standing rigging GL (N)
D_{n+3}	10665.4	2.5	26663.4
V_{n+2}	10068.9	2.5	25172.3
D_{n+2}	7367.7	2.5	18419.3
V_{n+1}	16839.7	2.5	42099.2
D_{n+1}	8920.3	2.5	22300.7
V_n	25014.0	2.5	62534.9
D_n	10209.0	2.5	25522.5

The working loads of the shrouds are calculated analytically for the four conditions by decomposing geometrically the transversal forces calculated before on each shroud. For the dimensioning of each shroud, the actual value of tension is multiplied by a reserve factor, suggested to be ≥ 2.5 from the guideline. These values are reported in Table 4.19-4.22 respectively, for each condition.

Third case: mainsail only

Table 4.20: Third case: mainsail only

Item ID	Shroud tension (N)	RF reserve factor GL >= 2.5 (-)	Dimensioning of standing rigging GL (N)
D_{n+3}	1092.3	2.5	2730.8
V_{n+2}	1031.2	2.5	2578.1
D_{n+2}	4903.7	2.5	12259.3
V_{n+1}	5526.8	2.5	13817.1
D_{n+1}	10053.7	2.5	25134.2
V_{n}	14739.7	2.5	36849.3
D_{n}	15881.9	2.5	39704.9

Fourth case: jib only

Table 4.21: Fourth case: jib only

Item ID	Shroud tension (N)	RF reserve factor GL >= 2.5 (-)	Dimensioning of standing rigging GL (N)
D_{n+3}	8671.6	2.5	21678.9
V_{n+2}	8186.6	2.5	20466.5
D_{n+2}	5990.4	2.5	14975.9
V_{n+1}	13691.6	2.5	34229.1
D_{n+1}	7252.7	2.5	18131.8
V_{n}	20337.8	2.5	50844.4
D_{n}	8300.5	2.5	20751.2

4.4.3 Dimensioning of the standing rig made of steel rod

Knowing the values of the possible maximum axial forces in each shroud, it is possible to get the diameter of each part knowing the properties of the material adopted. The material Nitronic 50 is used for the shrouds, as suggested in the guideline [1]. Its main proprieties are reported in Table 4.23*.*

Table 4.22: Nitronic 50 properties

Parameters	value	unit
Density	7880	(kg/m^3)
Ultimate tensile	730	(N/mm^2)
Tensile yield strength	420	(N/mm^2)
Reserve factor steel	1	(%)
Elongation	35	(%)
Reduction of area	55	(%)

The required area of each shroud is calculated from the Hooke's law: $\sigma = {}^{Axial\ force}/_{Required\ area}$

The dimensioning is related to the ultimate break load specified by the manufacturer and the used reserve factors are valid for Nitronic 50. Table 4.24 lists the minimum area required for each section and the adopted diameter. The axial force adopted is the maximum value between the four conditions considered.

Table 4.23: First round diameters of shrouds

Shroud/stay part	Max. load tension calculated (N)	Minimum area required (mm^2)	Diameter (mm)	Diameter used (mm)	Worst contribution
$D_{n\,3}$	26663.4	36.5	6.82	7	Spinnaker
$V_{n\,2}$	25172.3	34.5	6.63	6.75	Spinnaker
$D_{n\,2}$	18419.3	25.2	5.67	6.2	Spinnaker
$V_{n\,1}$	42099.2	57.7	8.57	9	Spinnaker
$D_{n\,1}$	25134.2	34.4	6.62	6.65	Main sail
V_n	62534.9	85.7	10.44	10.7	Spinnaker
D_n	39704.9	54.4	8.32	8.45	Main sail
Forestay	236694.3	324.2	20.32	20.4	
Aft stay	170160.4	233.1	17.23	17.3	

The diameters are calculated in this first round analytically. In later computation, some diameters will be changed, because some parts of the shrouds are over stressed in the quasi-static analysis with the software *Ansys* using the forces of the wind as input.

4.4.4 Dimensioning of the mast's panel

As presented, the mast is chosen to be 20.7 meters with three pairs of spreaders and stepped deck. The total length of the mast is divided into four panels with an equal length. The dimensioning of the mast can be divided into two parts. The first one is finding the required minimum inertia for each panel. This part is done according to the formulation of the reference. Starting data are reported in Table 4.25, and values of the transversal inertia are shown in Table 4.26. $PT = 1.5 * RM/b$ is given from the reference [2] and is representing the compression force present on the bottom of the mast.

Table 4.24: Starting data, mast panel's dimensioning

$RM_{(30°)}$	89537	(Nm)
PT	70687	(N)
$b_{\text{max at mast section}}$	1.90	(m)

Table 4.25: Mast panel's transversal inertia

Mast panel	Length (m)	Height from foot mast (m)	$PT_{adjusted}$ (-)	I_x (mm^4)
$Panel_0$	5.175	5.175	70686.9	7411247.4
$Panel_1$	5.175	10.350	55808.3	5903597.6
$Panel_2$	5.175	15.525	46595.4	4929027.9
$Panel_3$	5.175	20.700	39843.9	4214828.1

As shown in Table 4.26, the value of PT for the transversal inertia is adjusted removing from panel 1 to panel 3 the down compression of each diagonal shroud. The value of the longitudinal inertia is shown in Table 4.27.

Table 4.26: Mast panel longitudinal inertia

h	20.700	(m)
I_y	34756194.9	(mm^4)

After knowing the transversal and longitudinal inertia, it is necessary to choose the mast. It is taken as example for the mast profiles the table presented in the Principle of Yacht Design reference [2]. In the reference entering with the required minimum inertia the mast section and wall thickness are obtained. The final values for the mast are reported in Table 4.28.

Table 4.27: Mast final properties

Length (mm)	Breadth (mm)	I_y (cm^4)	I_x (cm^4)	Wall thickness (mm)	Weight (kg/m)	Total weight (kg)
274.0	185.0	3650	1650	4.9	10.32	213.624

Regarding the material used for the mast construction, for the dimensions of the mast studied in this work, aluminum alloy is usually used for both the mast and the spreaders. The proprieties of the aluminum are shown in Table 4.29.

Table 4.28: Aluminum physical properties

Ultimate tensile	310	(N/mm^2)
Yield strength	276	(N/mm^2)
Reserve factor steel	0.75	(%)
Density	0.0027	(kg/cm^3)

4.5 Pretension of the rig

The pretension of the rig is set to avoid slack of the shrouds of leeward side and in normal sailing condition is done for safety reasons. According to the reference [1], the pretension must be set in order to have tension also in the leeward side when sailing at heeling angles at or below the "SWA". The "Safe Working Angle (SWA)" generally represents a heeling angle of 30°.

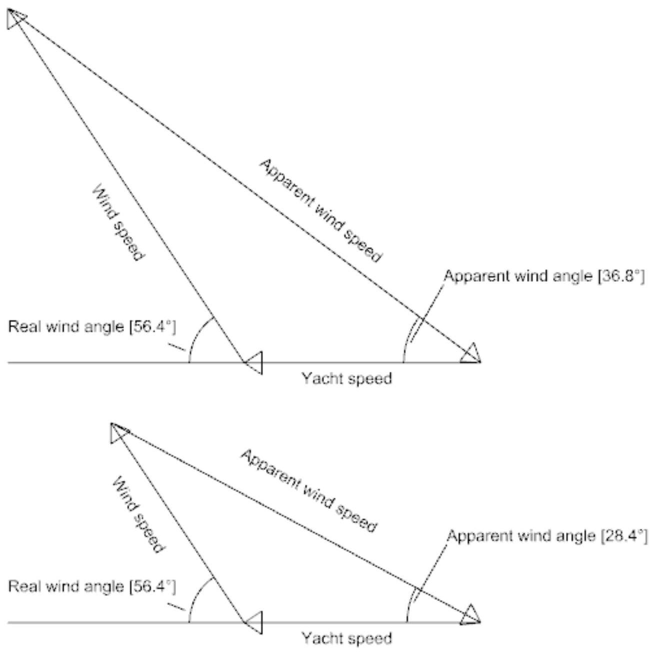


Figure 4.6: Wind flow at different mast height

The second aim of the pretension is to bend the mast tube in order to make the main sail working with a good shape in the top part of it. When the main sail is hoisted the top part is receiving a faster flow of wind because the wind flow is more undisturbed. Since the speed of the yacht is equal, in the top part of the sail the apparent wind angle with the sail will be bigger so the sail must be more open rather than down near the boom. The idea is sketched in Figure 4.6.

The typical configuration of the mast tube is bending backwards; staying almost straight for the first half and accentuating the bend in the top part.

According to the guideline [1], it is also important to tension the fore stay at least 66695.8 N, in order to give the jib a sag of less than 1%. As the rig is designed, it is possible to make the proper pretension by giving a displacement to the position of the attacks of stays, low verticals, and low diagonals.

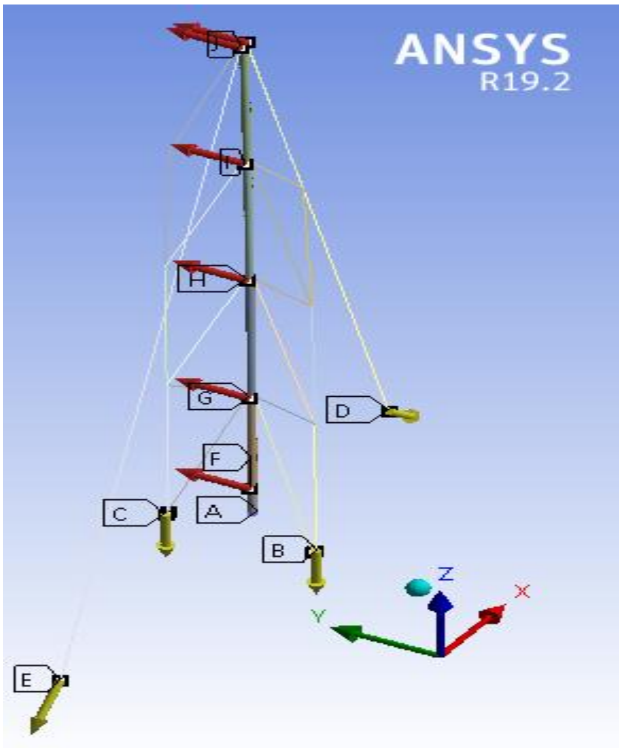


Figure 4.7: Pretension rig sketch of forces and displacement

The condition to obtain the proper pretension is the one with the combination of main sail and jib with a heeling moment of 30°.

The software *Ansys* is used to get the deformed shape of the mast and the tension in each shroud and stays. Few words must be said about the element type used for the FEM analysis. It is also important to mention the papers [5,12, 28] in which the study of the rig or sail deformation is carry on with the same software or for the dynamic response with the software LS-DYNA.

Regarding the mast tube is design as element type: SHELL 181. It overall considers 6734 elements and 6782 modes. All the shrouds, stays and spreaders are design as element type: BEAM 188. The two stays consider in total 277 nodes and 136 elements. Dn considers 81 nodes and 40 elements, Vn considers 61 nodes and 30 elements, Dn_1 considers 75 nodes and 37 elements, Vn_1 considers 57 nodes and 28 elements, Dn_2 considers 77 nodes and 38 elements, Vn_2 considers 57 nodes and 28 elements, Dn_3 considers 75 nodes and 37 elements. Regarding the spreaders: spreaders 1 and 2 considers 27 nodes and 13 elements and spreader 3 considers 25 nodes and 12 elements.

The forces are applied in six different points. The force of the main sail is divided between tack (F), spreader 1 (G), spreader 2 (H), spreader 3 (I), main sail head (J). The force of the jib on the mast is just transmitted from the jib head (K). The mast base is fixed and is identified by the position (A). The attack position of the forestay is identified by (D), backstay (E), lower vertical (B) and lower diagonals (C). Figure 4.7 clearly shows these positions, direction of forces and displacement on the mast rig. The perfect combination of the six points in which the displacement is given (D, E, B and C), is the result of a complex simulation in which every time the displacement is changed in order to satisfy the bend of the mast but also to avoid slack and not over tension the shrouds.

The forces applied at “SWA” angles of the main sail are reported in Table 4.30, and the forces of jib are shown in Table 4.31. The displacements, in “z” direction, given to the four positions of attacks that make pretension in the rig, are shown in Table 4.32. The result of the tensions of all components of the rig are shown in Table 4.33. The final shape of the mast tube and the rig is shown in Figure 4.8.

Table 4.29: Distribution of transversal sail forces of the mainsail

Application of the force	Distribution factor c_{im} (-)	F_{im} (N)
clew (not on rig)	0.16	608.8
tack	0.09	324.1
spreader 1	0.33	1252.2
spreader 2	0.24	915.3
spreader 3	0.14	545.6
main head	0.04	145.3

Table 4.30: Distribution of the transversal sail forces of jib

Application of the force	Distribution factor c_{if} (-)	F_{if} (N)
tack (not on rig)	0.40	2126.4
clew (not on rig)	0.29	1573.0
main head	0.31	1636.3

Table 4.31: Displacement of the pretension of shrouds and stays

Attack part	Displacement (mm)
V_n	-27.0
D_n	-10.0
Forestay	-28.3
Back stay	-54.4

Table 4.32: Tension result of the pretension

Component windward side	Axial tension (N)	Component leeward side	Axial tension (N)
V_n	30280.0	V_n	10752.0
D_n	17786.0	D_n	4234.4
V_{n+1}	13253.0	V_{n+1}	2348.0
D_{n+1}	18085.0	D_{n+1}	8917.5
V_{n+2}	5103.4	V_{n+2}	34.5
D_{n+2}	8656.5	D_{n+2}	2452.7
D_{n+3}	5358.2	D_{n+3}	33.0
Fore stay	70560.0		
Back stay	48031.0		

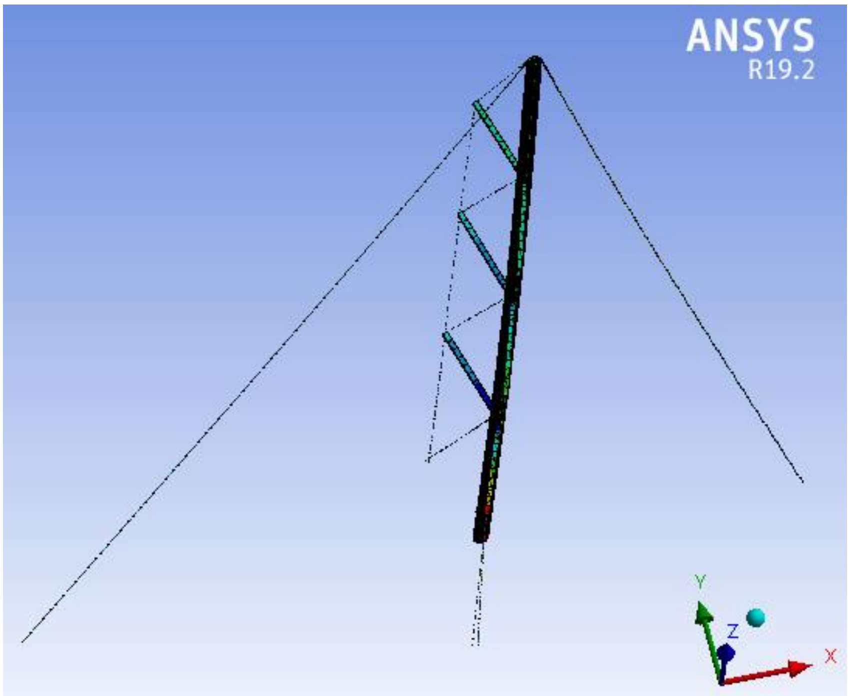


Figure 4.8: Final shape of the mast

4.6 Numerical computation for sail and rig aerodynamic

The numerical computation of the wind force for each sail is performed according to the *G. Hazen* model, from the reference [2].

The wind force is calculated for three different sails and four combinations: Mainsail with jib, spinnaker, main sail only and jib only. This section is divided into two main parts. The first is the calculation of forces for each sail and each combination, following the model described before. The second one is dividing the total force for each sail and applying it to defined points on the rig and the study of its behavior.

4.6.1 Calculation of the wind force generated

With the coefficients of lift and drag given from the model, the total lift/drag for each condition is calculated by multiplying the area of each sail with the corresponding coefficient, summing up the values on all sails and dividing in the end with the nominal area. The coefficient value of drag is composed by the sum of: Viscous/parasitic drag; induced drag and drag of mast and topsides. These values are given in Table 4.34 – 4.37 for the four conditions.

Table 4.33: Lift and drag coef. for mainsail and jib

Angle (°)	C_{Lift} (-)	C_{DP} (-)	C_{DI} (-)	C_{DO}(-)	C_{Drag} (-)
27	1.381	0.018	0.133	0.1217	0.273
50	0.888	0.187	0.055	0.1217	0.364
80	0.554	0.416	0.025	0.1217	0.563
100	0.364	0.428	0.011	0.1217	0.560
180	0.000	0.385	0.000	0.1217	0.507

Table 4.34: Lift and drag coef. for spinnaker

Angle (°)	C_{Lift} (-)	C_{DP} (-)	C_{DI} (-)	C_{DO}(-)	C_{Drag} (-)
27	0.000	0.000	0.000	0.1217	0.122
50	1.500	0.250	0.157	0.1217	0.528
80	1.000	0.900	0.081	0.1217	1.102
100	0.850	1.200	0.058	0.1217	1.380
180	0.000	0.660	0.000	0.1217	0.782

Table 4.35: Lift and drag coef. for mainsail only

Angle (°)	C_{Lift} (-)	C_{DP} (-)	C_{DI} (-)	C_{DO}(-)	C_{Drag} (-)
27	1.500	0.020	0.157	0.1217	0.298
50	1.500	0.150	0.157	0.1217	0.428
80	0.950	0.800	0.073	0.1217	0.994
100	0.850	1.000	0.058	0.1217	1.180
180	0.000	0.900	0.000	0.1217	1.022

Table 4.36: Lift and drag coef. for jib only

Angle (°)	C_{Lift} (-)	C_{DP} (-)	C_{DI} (-)	C_{DO}(-)	C_{Drag} (-)
27	1.500	0.020	0.157	0.1217	0.298
50	0.500	0.250	0.017	0.1217	0.389
80	0.300	0.150	0.007	0.1217	0.279
100	0.250	0.250	0.005	0.1217	0.377
180	0.000	0.500	0.000	0.1217	0.622

The values of lift and drag are calculated with the equation, as function of the wind speed, apparent wind angle and heel of the yacht.

$$Lift = \frac{1}{2} * \rho * C_{Lift} * Sail\ area * V_{Apparent}^2 \quad (4.1)$$

$$Drag = \frac{1}{2} * \rho * C_{Drag} * Sail\ area * V_{Apparent}^2 \quad (4.2)$$

The two coefficients are already calculated in the previous step for each apparent wind angle. The determination of the apparent wind speed as function of: V_1 and V_2 is more complicated.

The apparent wind velocity along the direction of motion (V_1) contains the yacht's speed, which is unknown. In this stage, an approximation is made by considering that the yacht's speed has been 0.6 the wind speed, till the achievement of the speed of $5.5\ m/s$ and then has been considered constant for this type of hull.

In the equation (3.31) of the apparent wind velocity along the direction of motion (V_2) is contained the heel angle of the yacht "Ø". The values of V_2 are calculated for all the possible heeling angles ranging from 0° to 50°. Then by multiplying the values of the side forces with the arm of action and intersecting these values with the righting moment of the yacht, it is possible to get the angle of the equilibrium condition.

Knowing the lift force and the drag force for each apparent wind angle, it is possible to determine the side force and the driving force. The driving force will be the force that makes the yacht move on, and the side force will be the one used to heel the yacht. The computation of the sail forces is performed for a wind speed ranging from $2\ m/s$ to $10\ m/s$ with a step of $2\ m/s$. For each speed, the angles of the apparent wind are: 27°, 50, 65°, 80°, 100°, 180°.

Table 4.38 lists the values of the side and driving forces and its condition of equilibrium for the condition of mainsail and jib. The summary of all other results is shown in the annex [F], for each wind speed is reported the condition of equilibrium of the sailboat and driving and side force found.

Table 4.37: Driving and side force for mainsail and jib

	2 m/s			4 m/s			6 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)
27	0.49	864.5	245.0	6.87	3424.5	970.4	15.42	7592.4	2151.5
50	0.41	392.7	206.3	3.12	1554.7	816.8	6.91	3447.1	1811.0
80	0.21	154.2	106.3	1.23	613.8	423.0	2.75	1370.8	944.7
100	0.13	69.3	64.6	0.55	276.7	258.0	1.25	621.0	578.9
180	0.05	0.0	23.2	0.00	0.0	92.6	0.00	0.0	208.4
Wind speed	8 m/s			10 m/s					
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)			
27	27.51	12664	3588.9	40.5	16440	4658.9			
50	12.11	6004.3	3154.5	18.5	8777.8	4611.6			
80	4.84	2412.1	1662.3	7.87	3921.0	2702.1			
100	2.21	1099.9	1025.4	3.84	1916.3	1786.4			
180	0.00	0.0	370.4	0.00	0.0	370.4			

In Figure 4.9, the curves of the moment generated by the wind force for each apparent wind angle and heel moment of the yacht for the condition of mainsail and jib are shown as an example. The green line represents the righting moment of the yacht. The intersection between the moments generated by the side force of the wind and the righting moment of the yacht, means the result of the equilibrium condition, for this case with a wind speed of 10 m/s and different apparent wind angles.

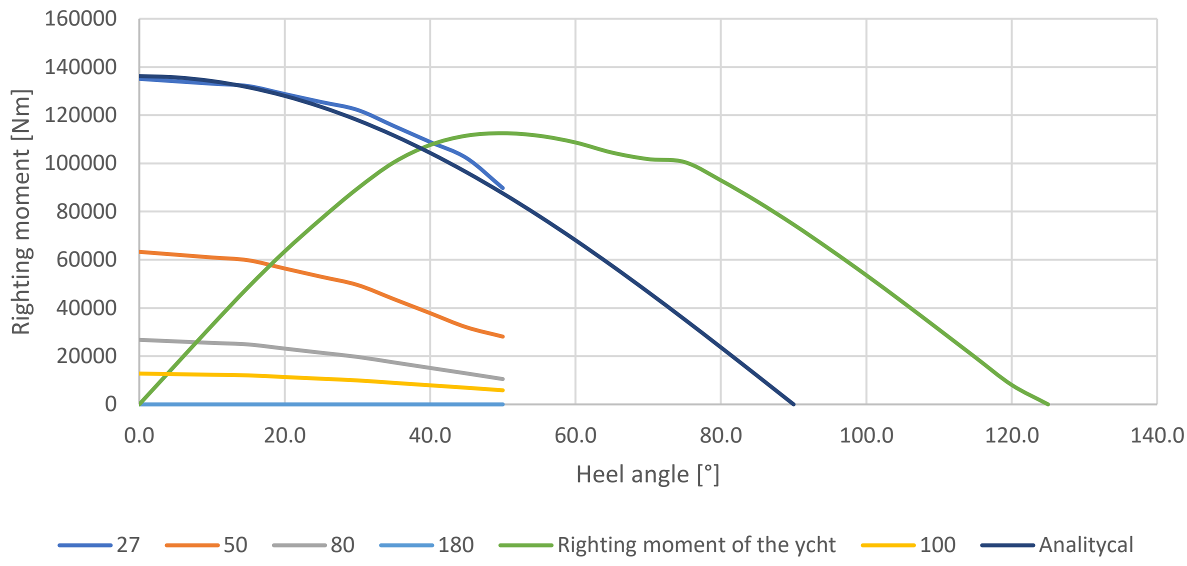


Figure 4.9: Heeling moment generated by wind force

In Figure 4.9 the blue line is calculated according to [1] and the results are similar to the *G. Hazen* model. The equation used is shown below.

$$HM_{(\emptyset)} = F_{(\emptyset)} * HA\ [Kgm] \tag{4.3}$$

where HA is the arm of the heeling moment [m].

$$F_{(\emptyset)} = 0.1 * (SA + ARIG) * V_a^2 * \cos(\emptyset): \tag{4.4}$$

Analytical formulation for side force, show in reference [1]

$$SA = ALAT + SAR \tag{4.5}$$

LAT: lateral area of the yacht over water level (calculated in rhino)

SAR: sail area of reference

ARIG: transversal area of the sail equipment (estimated)

4.6.2 Distribution of the forces on the rig

The G. Hazen model [2] is applying the force for each sail in its respectively barycenter, the following step is the decomposition of the forces from the sail and applying it in the points of the rig. The force of the jib is transmitted to the rig just from its main head, the claw and tack are directly applying it to the hull. The force of the mainsail is divided into: main head, spreader 1,2,3 and tack. The clew of the mainsail is transmitting its force to the boom and from it to the hull by boom's sheet, it is not considered directly applied to the rig.

The force is divided according to the same coefficient used, presented in the section 4.4.1, in order to get the same heeling moment by decomposing the force just applied in its barycenter in the different points of load. A side force and a driving force characterize each point. The values computed for each condition are shown in Table 4.40 for mainsail and jib. All other results are shown in annex [F]. Table 4.39 presents an example of how the data are presented for the condition of mainsail with jib and a wind speed of 10 m/s.

Table 4.38: Forces of mainsail and jib for 10 m/s

	Mainsail values						Jib values		
	Side direction						Side direction		
Apparent wind angle (°)	clew (not on rig) (N)	Tack (N)	sp. 1 (N)	sp. 2 (N)	sp. 3 (N)	main head (N)	clew (not on rig) (N)	tack (not on rig) (N)	main head (N)
ratio factor [-]	0.16	0.09	0.33	0.24	0.14	0.04	0.29	0.40	0.31
27	1227.1	653.3	2523.8	1844.9	1099.7	292.9	2594.0	3506.5	2698.5
50	655.1	348.8	1347.5	985.0	587.1	156.4	1385.0	1872.2	1440.7
80	292.6	155.8	601.9	440.0	262.3	69.9	618.6	836.3	643.6
100	143.0	76.1	294.2	215.0	128.2	34.1	302.3	408.7	314.5
180	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Drive direction						Drive direction		
Apparent wind angle (°)	clew (not on rig) (N)	Tack (N)	sp. 1 (N)	sp. 2 (N)	sp. 3 (N)	main head (N)	clew (not on rig) (N)	tack (not on rig) (N)	main head (N)
27	185.1	715.2	522.8	311.6	83.0	185.1	735.1	993.7	764.7
50	183.3	707.9	517.5	308.5	82.2	183.3	727.6	983.6	756.9
80	107.4	414.8	303.2	180.7	48.1	107.4	426.3	576.3	443.5
100	71.0	274.2	200.5	119.5	31.8	71.0	281.9	381.0	293.2
180	14.7	56.9	41.6	24.8	6.6	14.7	58.4	79.0	60.8

4.7 Quasi-static analysis

The main idea of the quasi-static analysis is to get the maximum stresses in the structure [25, 26]. It is performed with two different analysis, both of them are performed with the software Ansys [27]. The first one is performed by fixing the wind speed with its maximum value for each condition and changing the apparent wind angle. After the first analysis, the worst apparent wind angle is found. The second analysis is conducted by fixing the angle for each condition and changing the wind speed. Similar idea of this kind of analysis was carry on in [28].

It is considered a quasi-static analysis because for both the wind speed and apparent wind angle the values are changed with a ΔT of 1 second and kept for the same time step. Step of ΔT of 1 second is used for the spinnaker condition while changing the apparent wind angle.

4.7.1 Changing apparent wind angle

The apparent wind angle is changed according to complete a jibe and a taking, the two main maneuver in sailing in order to change the side of the force, from starboard to port side. The apparent angle of the wind is changing from 27º to -27º passing from 180° (with a jibe), and from -27º to 27º (with a tacking). This is applied just on the mainsail and jib.

For the spinnaker the angle is varying from 80º to -80º, completing just a jibe. It is impossible to do a tacking with this type of sail. For the condition of mainsail coupled with jib, the mainsail only and jib, the apparent wind angle is changing as shown in Figure 4.10 and for both conditions the wind speed is fixed as 10 m/s.

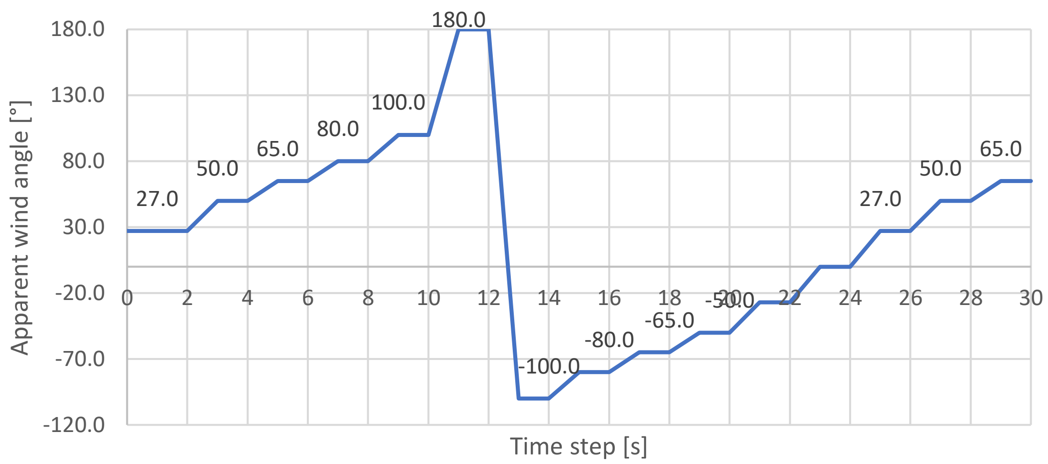


Figure 4.10: Apparent wind angle variation for mainsail and jib

For the condition of the spinnaker, the apparent wind angle is changing as Figure 4.11 and the wind speed is fixed as 8 m/s.

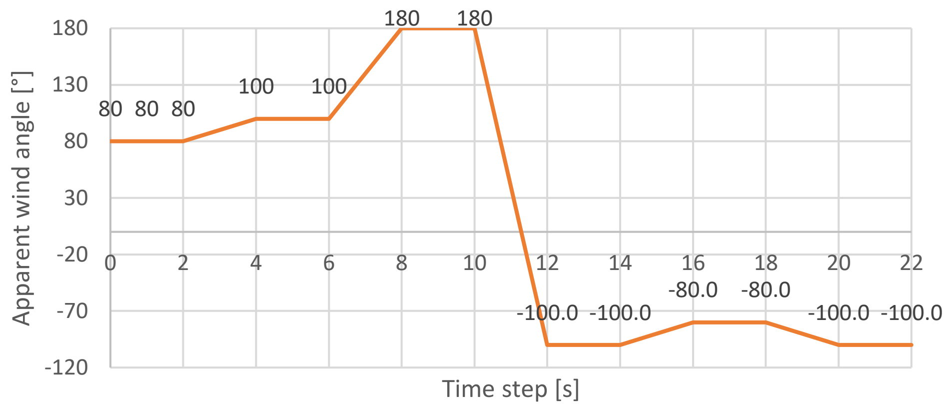


Figure 4.11: Apparent wind angle variation for spinnaker

The calculations are performed for all the conditions. The apparent wind angle that makes the worst axial forces on the shrouds is 27° for the sails: mainsail and jib; 80° for the spinnaker sail. Table 4.40 lists only the extreme values from the analysis in ANSYS.

For the mainsail, jib and spinnaker the forces applied tend to take into account situations very burdensome; it is not taken into account the referring of the sail area with the increasing of the wind speed. As seen in the table for the component: *Vn*, $Dn_{0\text{-}1}$ the value of the axial tension is above the yielding stress of the material *420 N/mm²*. It is necessary to increase the diameter of these two components in order to keep the value of the axial force at least above the *85%* of the yield stress. The components Dn_2 have a yield strength *17.8%* over the *85%* of the yield stress as mentioned before, so small changes will be processed.

Table 4.39: Extreme value of tension for the fourth condition

Components on upwind side	Mainsail and jib (N)	Mainsail only (N)	Jib only (N)	Spinnaker (N)	Yield strength (N/mm²)	Percentage of stresses (-)
Dn3	6157.7	2536.4	7740.9	9208.4	239.3	57.0%
Vn2	5865.1	2416.9	7371.3	8768.5	245.0	58.3%
Dn2	10985.0	8632.7	10186.0	11763.0	389.6	92.8%
Vn1	16206.0	10195.0	16958.0	19838.0	311.8	74.2%
Dn1	23244.0	20432.0	18496.0	20251.0	669.2	159.3%
Vn	38087.0	29433.0	34369.0	38900.0	432.6	103.0%
Dn	26097.0	21711.0	16535.0	18454.0	465.4	110.8%
Fore stay	70561.0	70322.0	70561.0	69649.0	215.9	51.4%
Back stay	49620.0	48587.0	49393.0	52190.0	222.0	52.9%

4.7.2 Diameters change

The change of the diameters is a complex process; it cannot be done at priori. Every time the diameters of the three components (*Dn_2, Dn_1, Dn* and *Vn*) are varied, the rig behaves differently because the stresses and deformation are redistributed differently in the structure.

The process to change the diameters is iterative; starting with the main idea that with the axial forces just calculated, the percentage of stress with the new diameters should be more of less about *75%* of the yield stresses. The process is run few times and diameters change in order to have all the values of the axial forces in each component over the *85%* of the yield stress of the material used.

The process to change the diameters is run on the condition with mainsail and jib; later the others are checked and may be corrected. The final values in the end of this computation are reported in the table. As said before, this analysis is done fixing the wind speed to the highest values possible for the sails used and the apparent wind angle varies.

Table 4.40: Diameter change

Components on upwind side	Mainsail and jib (N)	Mainsail only (N)	Jib only (N)	Spinn aker (N)	Yield strength (N/mm²)	% of stress (-)	Second diameters (mm)	First diameters (mm)
Dn3	7056	3434	8544	9992	259.6	61.8%	7	7
Vn2	6717	3270	8133	9512	265.8	63.3%	6.75	6.75
Dn2	12511	10145	11845	13470	268.0	63.8%	8	6.2
Vn1	18483	12507	19271	22176	348.6	83.0%	9	9
Dn1	32808	30046	27438	29356	358.1	85.2%	10.8	6.65
Vn	49347	40776	45085	49793	347.9	82.8%	13.5	10.7
Dn	30340	25919	19730	21710	292.1	69.5%	11.5	8.45
Fore stay	70243	70008	70243	69330	214.9	51.2%	20.4	20.4
Back stay	47838	46731	47694	50467	214.7	51.1%	17.3	17.3

4.7.3 Increasing wind speed

With the first analysis done, now the software is run fixing the apparent wind angle found. The main idea of this analysis is increasing and decreasing the wind speed in order to load and discharge the rig and study its behavior.

For the condition of mainsail coupled with jib, the mainsail only and jib, the wind speed is made vary as Figure 4.12 and for both conditions, as said, the apparent wind angle is fixed as 27°.

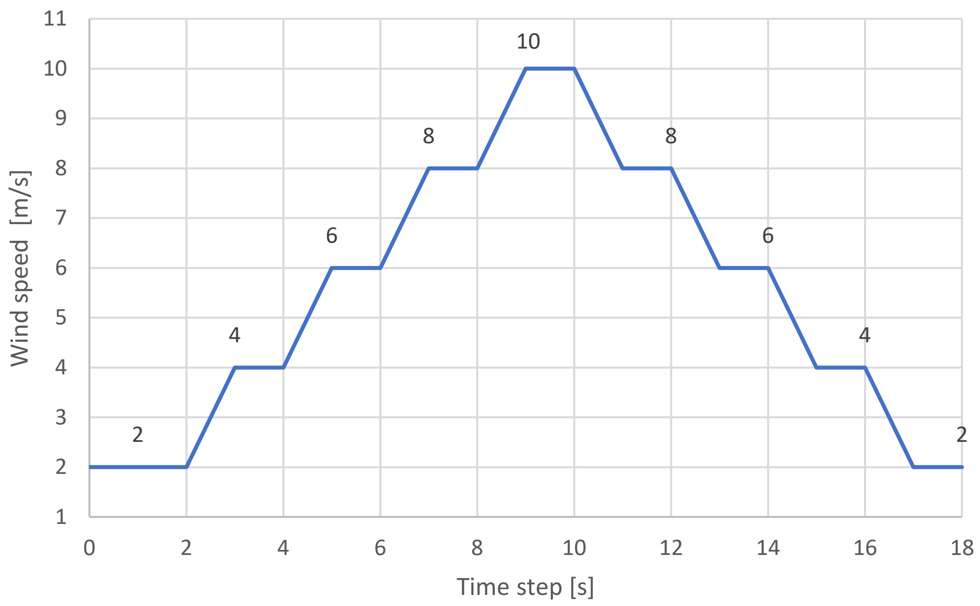


Figure 4.12: Wind angle variation for mainsail and jib

For the condition of the spinnaker sail, the wind speed is made vary as Figure 4.13 and the apparent wind angle is fixed at 80°.

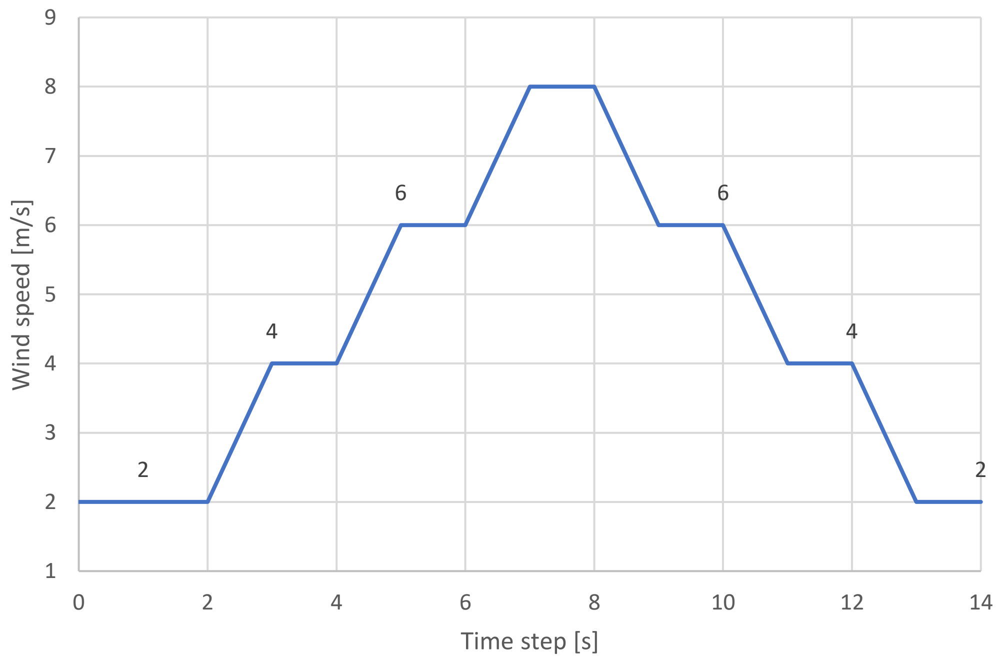


Figure 4.13: Wind angle variation for spinnaker

With the quasi-static analysis run for the increase and decrease of the wind speed, the values of the maximum axial forces are shown in Table 4.41.

Table 4.41: Quasi-static analysis, wind speed change

Components on upwind side	Mainsail and jib (N)	Mainsail only (N)	Jib only (N)	Spinnaker (N)	Yield strength (N/mm^2)
Dn3	6996.7	3553.8	8541.2	9992	259.6
Vn2	6661.3	3384.1	8130.6	9511.6	265.8
Dn2	12579	10140	11849	13470	268.0
Vn1	18491	12496	19272	22176	348.6
Dn1	18491	31127	27444	29356	339.8
Vn	49477	41782	45091	49793	347.9
Dn	30453	27125	19736	21710	293.2
Fore stay	70039	70159	70175	69943	214.7
Back stay	48623	46582	47743	50460	214.7

As seen for the condition of the 10 m/s for mainsail and jib and 8 m/s for the spinnaker of wind speed, the values of the axial forces are almost similar.

As it is possible to notice, the table reporting the maximum axial forces of the two cases of study gives different values of them; this is possibly caused by the fact that the structure is loaded with different cycles so, it will react differently changing the distribution of the forces inside the structure.

4.7.4 Mast and spreaders stresses

The dimensioning of the mast was done at previous stage starting from the righting moment at the yacht and considering the partition of the mast with spreaders and shrouds, the minimum required inertia, longitudinal and transversal is given as an output

The minimum required inertia is important to give sufficient stiffness for the mast to bend but not to break. The main possibility for a mast of a sailboat to break is caused by the buckling. The stresses in the mast are divided into four panels; considering the fact that for each panel the minimum required inertia should be different, following the formulations illustrated before, increasing the values for the lower panels.

The mast is made of aluminum and is considered a yield stress of 276 *MPa* considering a safety coefficient of 0.85. With the software *Ansys* the equivalent von-Mises stresses are checked, and three different values are given: minimum, maximum and average values of the stresses for each panel. The values are shown in the Table 4.43.

Table 4.42: Mast panel's von-Mises stresses (MPa)

Condition: Mainsail and jib			
Component	Stresses (Ansys workbench) Minimum (Max)	Stresses (Ansys workbench) Maximum (Max)	Stresses (Ansys workbench) Average (Max)
Panel 3	3.65	315.78	35.09
Panel 2	15.41	144.84	37.23
Panel 1	23.55	292.24	48.26
Panel 0	0.00	252.79	54.80
Condition: Mainsail only			
Component	Stresses (Ansys workbench) Minimum (Max)	Stresses (Ansys workbench) Maximum (Max)	Stresses (Ansys workbench) Average (Max)
Panel 3	2.50	316.31	35.10
Panel 2	15.98	140.37	37.24
Panel 1	24.49	252.78	48.20
Panel 0	0.00	215.43	54.88
Condition: Jib only			
Component	Stresses (Ansys workbench) Minimum (Max)	Stresses (Ansys workbench) Maximum (Max)	Stresses (Ansys workbench) Average (Max)
Panel 3	3.88	316.31	35.19
Panel 2	13.94	134.22	37.32
Panel 1	22.45	291.12	48.27
Panel 0	0.00	256.04	54.05
Condition: Spinnaker			
Component	Stresses (Ansys workbench) Minimum (Max)	Stresses (Ansys workbench) Maximum (Max)	Stresses (Ansys workbench) Average (Max)
Panel 3	3.69	315.43	35.15
Panel 2	13.85	147.61	37.29
Panel 1	22.52	315.99	48.49
Panel 0	0.00	278.80	54.41

As it is possible to notice, for all the condition and each panels the maximum value of the stress is found to be over the yield stress of the aluminum. In fact, this is not occurring because as the mast in the software is modelled as a shell, no reinforcement or supporting plate which may distribute the stresses better, are considered.

This is possible to be noticed in Figure 4.14-4.16, where all parts of the mast are subjected to stress lower than 275 *MPa* except the area where shrouds and spreaders are connected to the mast. Therefore the stresses in these points are transmitted just from the one node leading to a stress concentration higher than it would be in the reality.

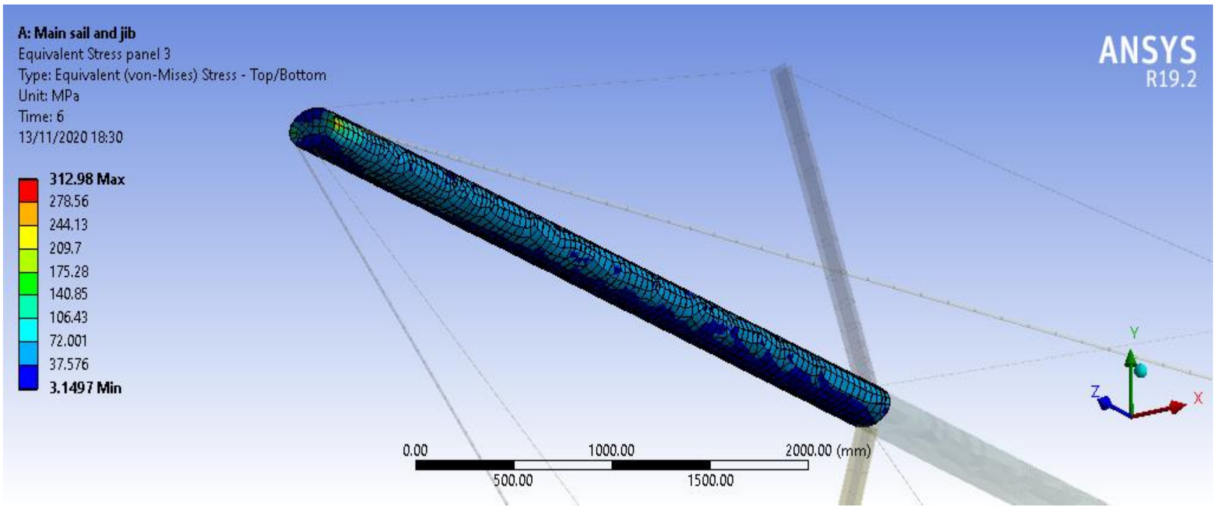


Figure 4.14: Panel 3, von-Minses stresses

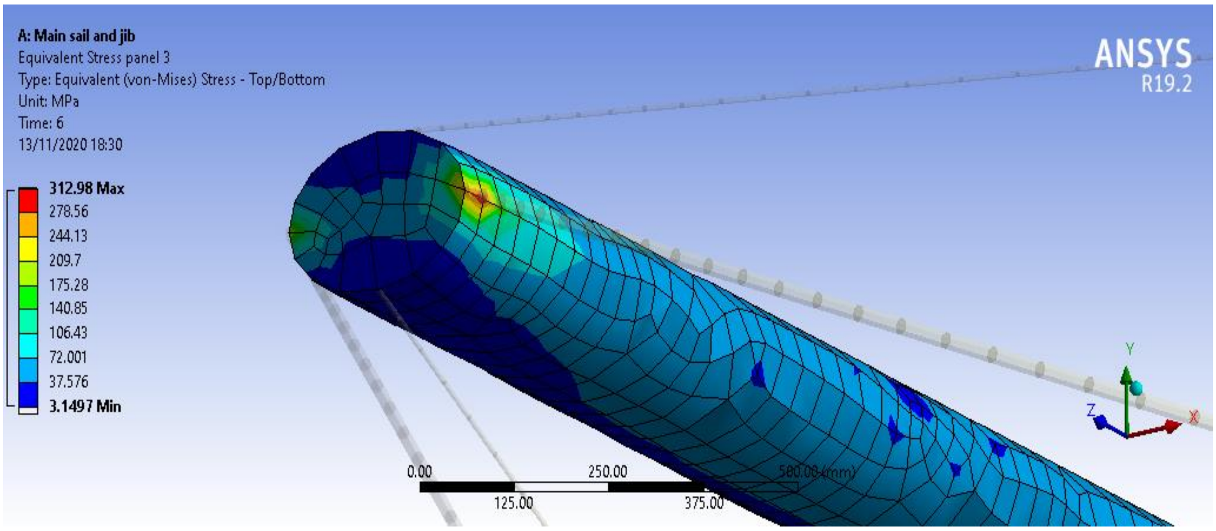


Figure 4.15: Panel 3, von-Minses stresses (zoom)

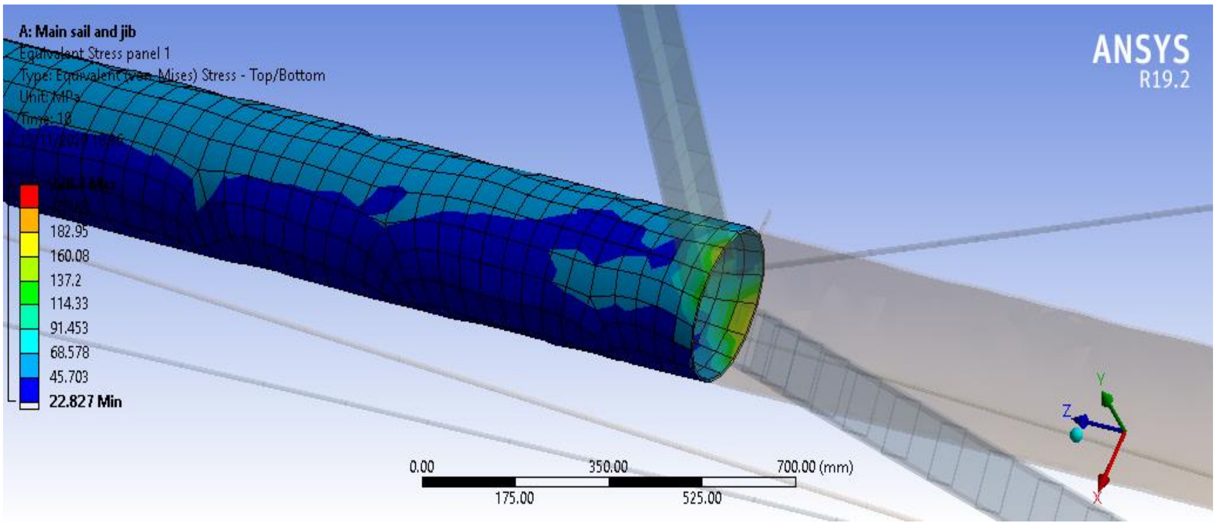


Figure 4.16: Panel 2, von-Minses stresses

It is more important to notice for this analysis that overall, the mast is not subjected to high values of stress holding an average value lower of 55 *MPa.* Similar to the mast, also the spreaders are checked with the software *Ansys*. The spreaders are useful to avoid long unsupported spans of the mast and are important to deflect the shrouds for better support the mast. According to their configuration the spreaders are loaded just in compression.

Table 4.43: Spreaders properties

Breadth	120.0	(mm)
Height	70.0	(mm)
Profile area	1216.0	(mm^2)

The profile of the spreaders is taken with similarity for similar type of sailboat and dimensions. The three levels of spreaders have all the same profile, chosen to be rectangular for a simpler design in the software and its properties are reported in Table 4.44.

The values of the axial forces are reported in Table 4.45 with the yield stress of each spreader. The value of the yield stresses as it can be seen are all over the 40 *MPa*, an acceptable value for the structure and for the buckling possibility.

Table 4.44: Spreaders axial forces

Condition: Mainsail and jib

Component	Axial force (Ansys workbench) Upwind (N)	Yield strength (N/mm^2)	Axial force (Ansys workbench) Downwind (N)	Yield strength (N/mm^2)
Spreader 3	-1959.9	9.074	-788.75	3.652
Spreader 2	-4516.5	20.910	-1675.10	7.755
Spreader 1	-11157.0	51.653	-6415.20	29.700

Condition: Mainsail only

Component	Axial force (Ansys workbench) Upwind (N)	Yield strength (N/mm^2)	Axial force (Ansys workbench) Downwind (N)	Yield strength (N/mm^2)
Spreader 3	-995.46	4.609	-915.01	4.236
Spreader 2	-3561.70	16.489	-1805.90	8.361
Spreader 1	-10556.00	48.870	-6546.10	30.306

Condition: Jib only

Component	Axial force (Ansys workbench) Upwind (N)	Yield strength (N/mm^2)	Axial force (Ansys workbench) Downwind (N)	Yield strength (N/mm^2)
Spreader 3	-2392.60	11.077	-783.55	3.628
Spreader 2	-4315.10	19.977	-1696.80	7.856
Spreader 1	-9286.10	42.991	-6477.30	29.988

Condition: Spinnaker

Component	Axial force (Ansys workbench) Upwind (N)	Yield strength (N/mm2)	Axial force (Ansys workbench) Downwind (N)	Yield strength (N/mm2)
Spreader 3	-2799.00	12.958	-863.23	3.996
Spreader 2	-4914.40	22.752	-1795.10	8.311
Spreader 1	-9929.10	45.968	-6582.20	30.473

4.8 Dynamic analysis

After the quasi-static study of the structure, a dynamic analysis is performed. First the three natural frequencies of the structure with a modal analysis are found and later the wind speed is schematized as a spectrum in time domain and applied to the structure. Paper [29] carry on the same simulation for an offshore structure.

4.8.1 Modal analysis of the rig system

The modal analysis is carried out with the software *Ansys*, and the first three modes of vibration of the mast tube in the transversal and longitudinal plane (*Y0Z and X0Z*) are studied.

This type of study performed will be useful later because, applying the wind force on the rig as a spectrum, it is possible to find the frequencies of the wind spectrum that more come closer to the natural frequencies of the mast tube and may cause little resonance in the system. The modes of vibration are found for the transversal and longitudinal plane and are reported in Table 4.46.

Table 4.45: Global natural frequencies of the rig

First mode longitudinal [Hz]	2.039	First mode transversal [Hz]	7.640
Second mode longitudinal [Hz]	6.879	Second mode transversal [Hz]	9.859
Third mode longitudinal [Hz]	11.230	Third mode transversal [Hz]	14.889

The shape of the mast tube for the six condition is shown in Figure 4.17-4.22 taken from the software *Ansys.*

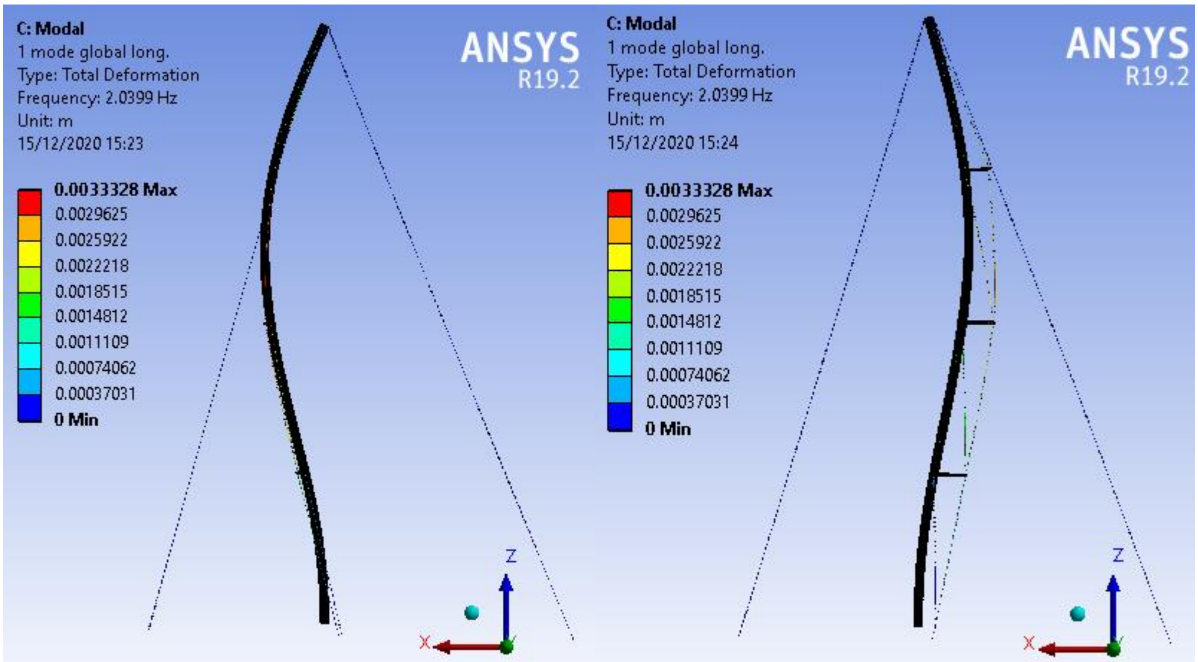


Figure 4.17: First mode longitudinal plane, 2.0399 Hz (zoom in 7.9e+2)

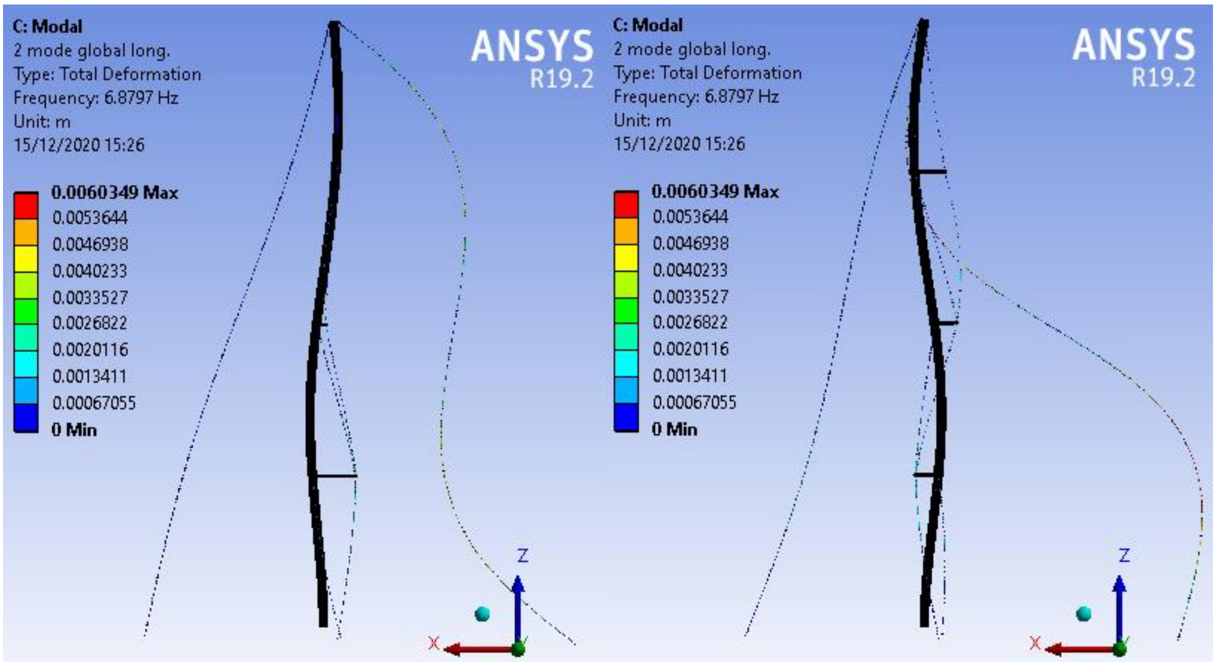


Figure 4.18: Second mode longitudinal plane, 6.8797 Hz (zoom in 4.6e+2)

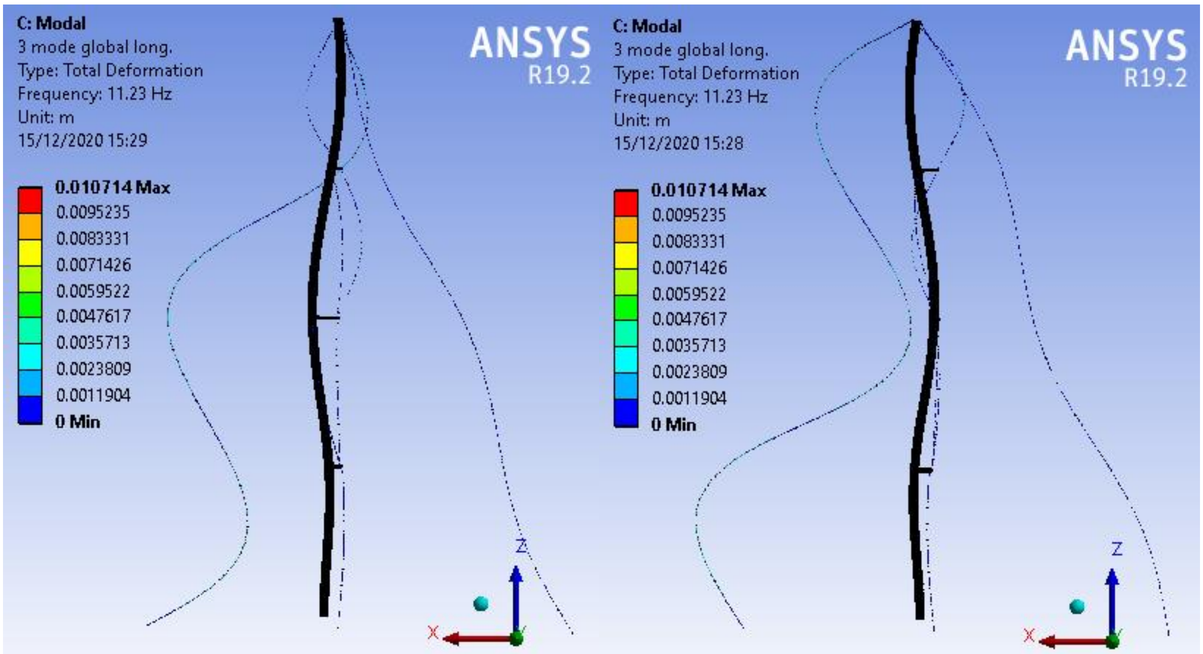


Figure 4.19: Third mode longitudinal plane, 11.23 Hz (zoom in 6.7e+2)

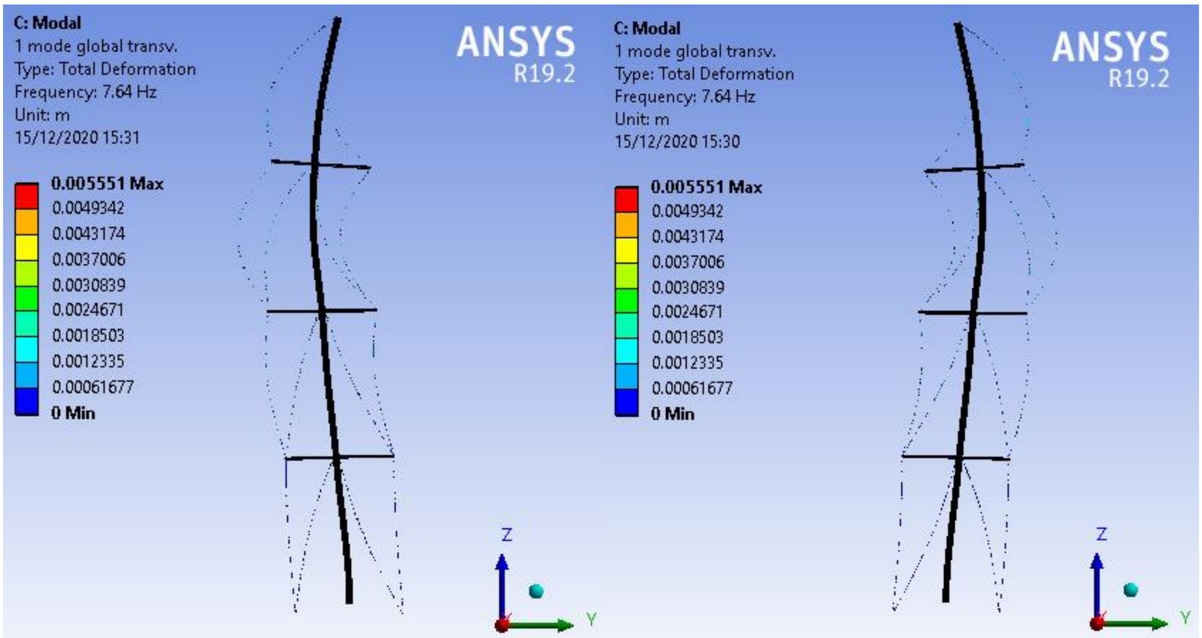


Figure 4.20: First mode transversal plane, 7.64 Hz (zoom in 1.3e+2)

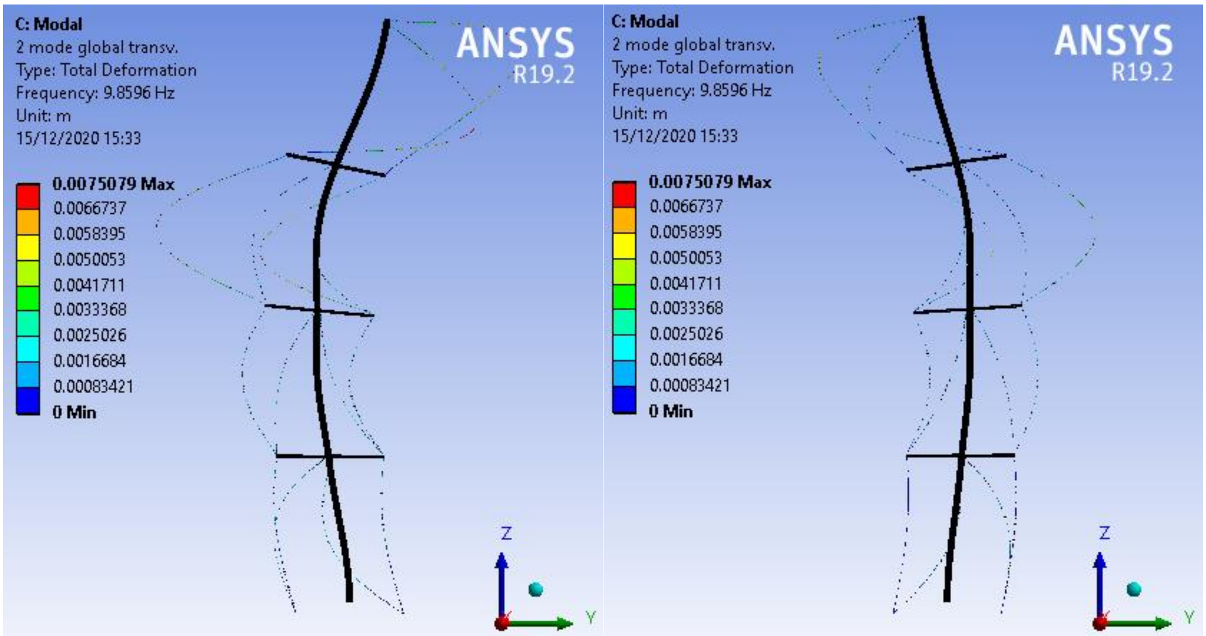


Figure 4.21: Second mode transversal plane, 9.8596 Hz (zoom in 7.4e+2)

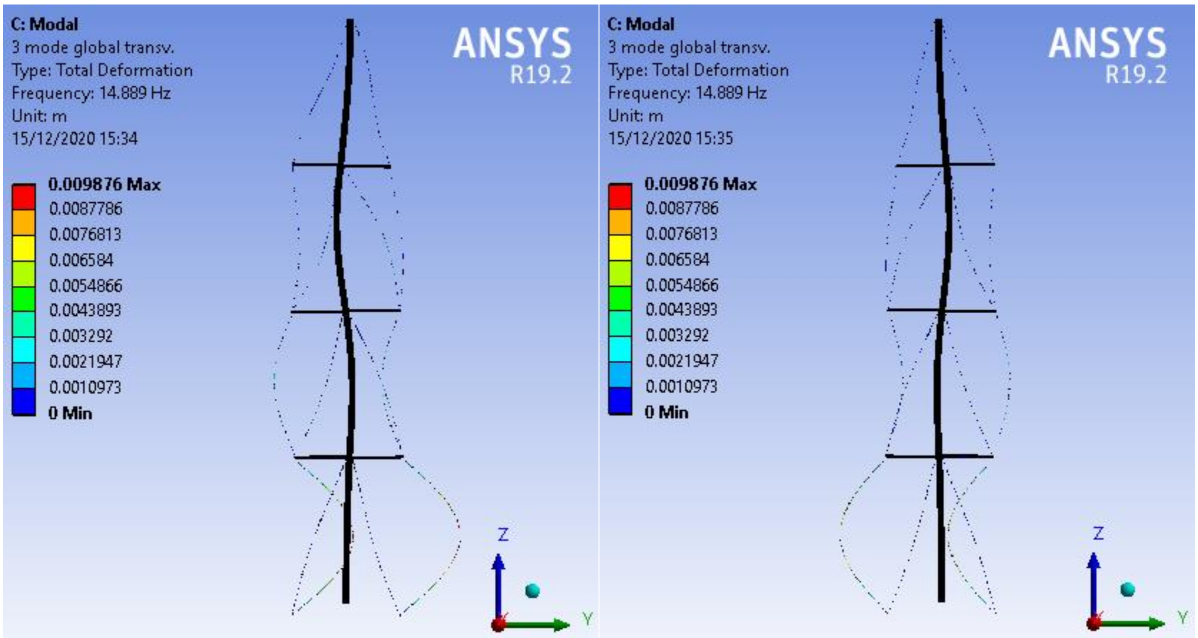


Figure 4.22: Third mode transversal plane, 14.889Hz (zoom in 2.2e+2)

4.8.2 Wind spectra generation

In the reference [1], the stationary component of the wind speed is considered as constant, equal to the mean wind speed $\bar{v}_m(t)$ like a simplification for the problem. This is considered acceptable if the simulation is carried out for small time period as *1, 10, 60 minutes*.

The turbulence is studied with a statistical approach, in which its main parts are: the turbulence length scale L_u, the distribution of the standard deviation σ_u. The spectral density of energy $S_{v_m}(f)$ represents the energetic contribution of the vortex in function of the frequency and is calculated according to the mean wind speed. The mean speed of the wind considered for the simulation is *9 m/s*, which is a good value for reaching gusts not over the 11 *m/s*. .

The turbulence length scale, described as: $L_u = 300\left(\frac{z}{300}\right)^{0.46+0.074\ln z_0}$; where z denotes the height above the ground or the sea water level, $z = 9\ m$ average position of the barycenter of the mainsail and jib. z_0 is the terrain roughness., the values is set as $z_0 = 0.0055\,m$ mean value between the two opposites. The distribution of the standard deviation is described as: $\sigma_u = \ I_{Ref} * (0.75 * \overline{v_m} + 5.6$; where $I_{Ref} = 0.14$ according to the normal turbulence model, NTU. The range of frequency considered for the short period is from $0\ Hz$ to $0.25\ Hz$. Figure 4.23 reports the graph for the Kaimal spectrum for the input given.

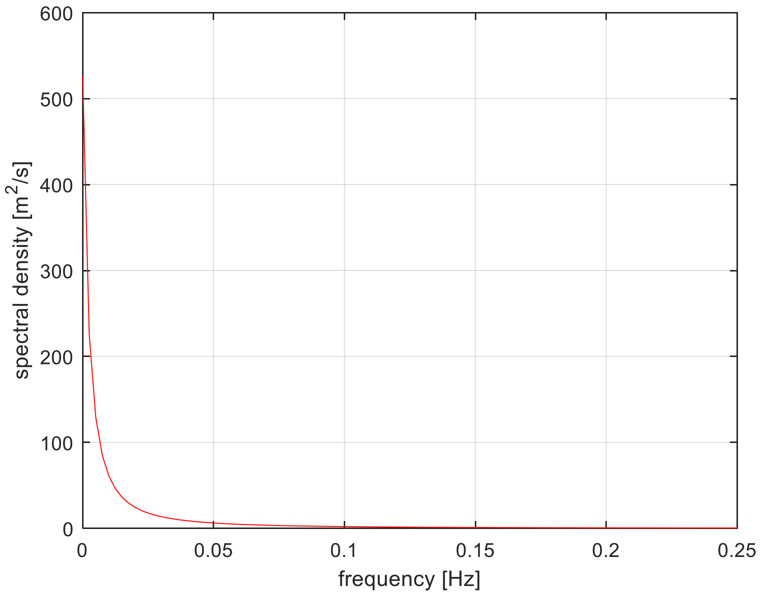


Figure 4.23: Kaimal spectrum

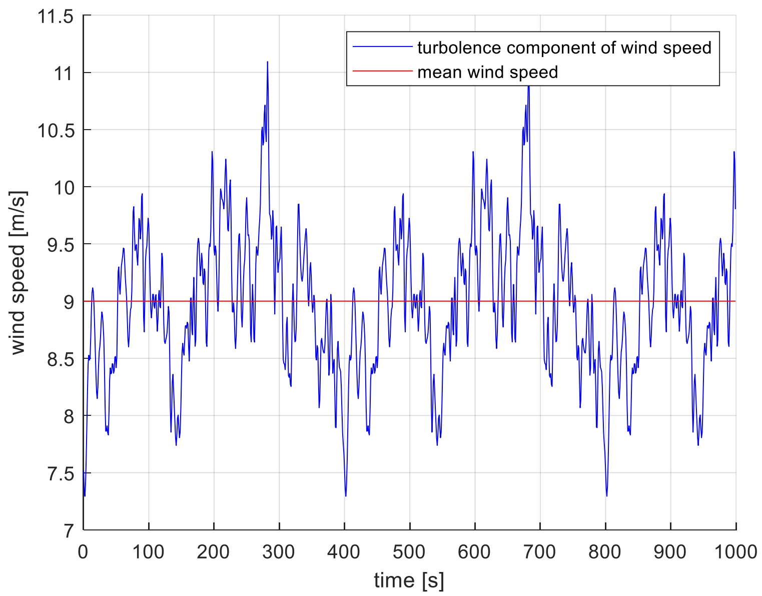


Figure 4.24: Time domain wind speed

To obtain the time domain wind speed, the turbulent wind speed $v_t(t)$ is calculated as the sum of the harmonics, where the amplitude A_i relative of the frequency f_i is calculated with the equation (4.6) and the phase φ_i is generated with a random variable between the interval $[-\pi; +\pi]$. It is also considered $f_0 = 0$ and $A_0 = \bar{v}_m$.

$$A_i = \frac{2}{\pi} * \sqrt{\frac{1}{2} * \left(S_{v_m}(f_i) + S_{v_m}(f_{i+1})\right) * (f_{i+1} - f_i)} \qquad (4.6)$$

The wind speed in time domain is obtained with the equation (4.8.2) as sum of the harmonics components.

$$v(t) = \sum_{i=0}^{n} A_i * \cos(2 * \pi * f_i * t + \varphi_i) \tag{4.7}$$

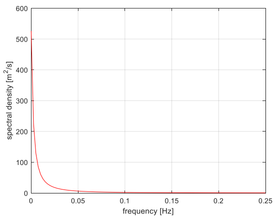
Figure 4.24 represents the sign described.

4.8.3 Wind spectra analysis

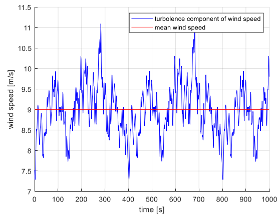
The wind spectra analysis is carried out just for the condition of mainsail and jib since it is the condition most used and full of information and data.

Scheme of the spectral analysis:

First step: the generation of the wind spectrum



Second step: the generation of the time domain from the wind spectrum



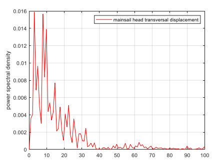
Third step: calculation of the forces, following G. Hazen model reference [2], generated by the wind on the mainsail and the jib for each *dt* = *1s*. Repartition of the forces from the barycenter of the two sails on the rig from: mainsail head, jib head, sp. 3, sp. 2, sp. 1 and tack.

Fourth step: input of the forces and simulation of the model of the software *Ansys*.

Collect of the displacement data output of mainsail head, sp. 3, sp. 2, sp. 1 and tack.

Simulation is carry out for *1000 s*.

Final step: the generation of the Fourier transformation to get the frequency response of the system and comparison with the modal analysis.



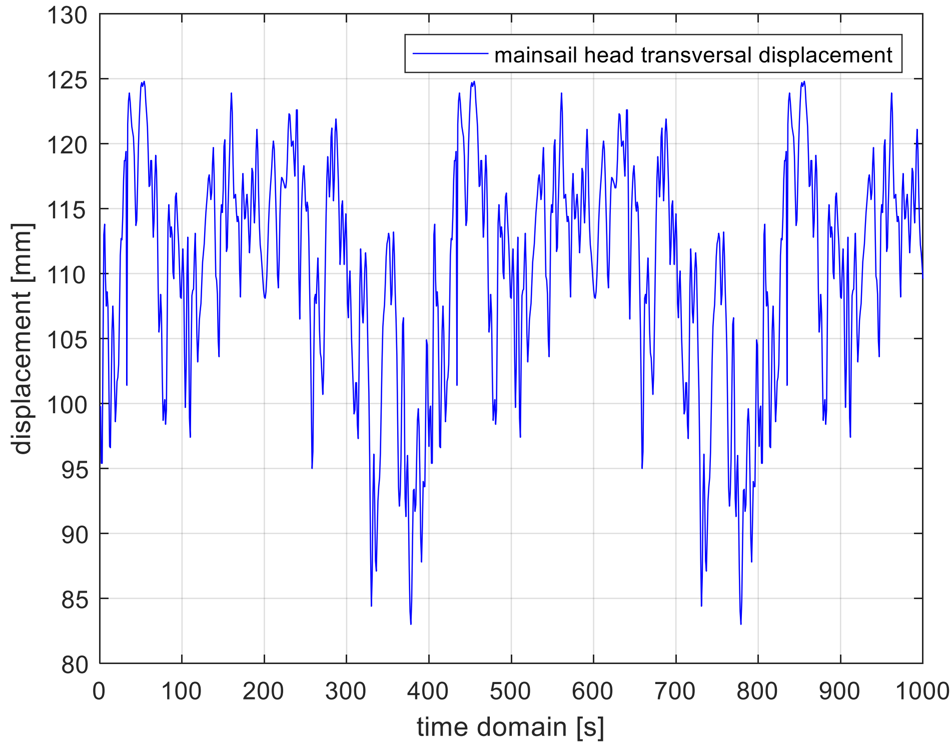


Figure 4.25: Mainsail head transversal displacement

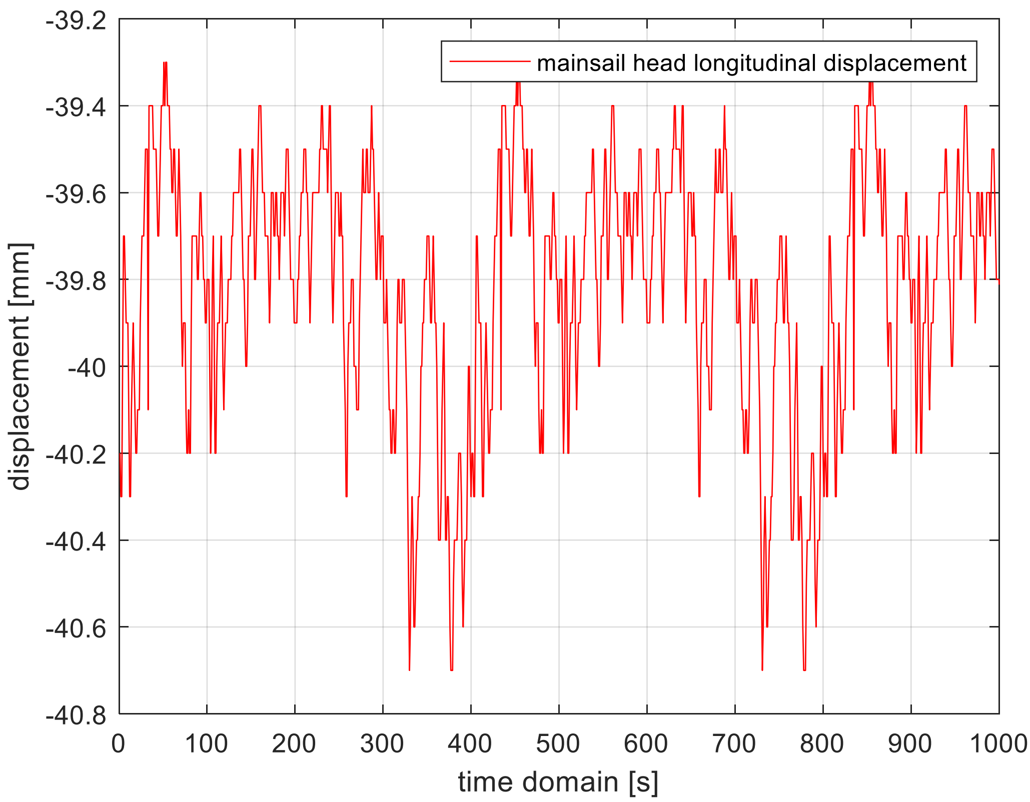


Figure 4.26: Mainsail head longitudinal displacement

The displacement output of the mainsail head, sp. 3, sp. 2, sp. 1 and tack are shown in the figure presented in the annex [D], [E]. In Figure 4.25-4.26, a sample of the mainsail head displacement for the *X* direction and *Y* direction in the plane *X0Y* is given

With the output data of the displacement, for the longitudinal and transversal displacement a Fourier transformation is done to convert the time domain signal into a frequency domain signal. The Fourier transformation is calculated in Matlab using the function fast Fourier transformation

The first step is to obtain the length of the time domain signal; then to get a good frequency resolution of the Fourier transformation the number of the length of the signal must be equal to two to power of the length of the signal. When the F. transformation is computed, it gives a symmetrical result; it is considered just the first half by removing the other one. The "x" axis is correctly converted into frequency and "y" axis is normalized to the amplitude.

All the five points for longitudinal and transversal displacement give the same frequency for each peak. The amplitude of the frequency is different and a bigger amplitude for the top of the mast is found reducing the value with a minimum in the tack point, being smaller the displacement for lower points.

In Figure 4.27-4.30 the frequency domain of the mainsail head and sp.1 for the longitudinal and transversal motion is given as an example. All the graphs are reported in the annex [B], [C].

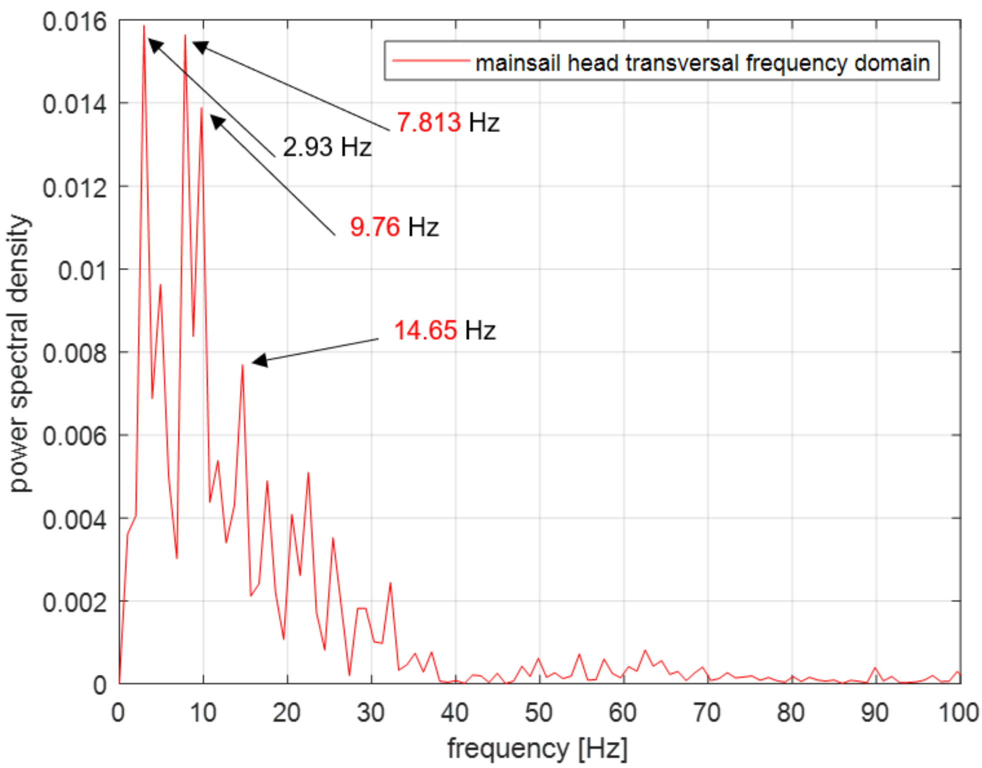


Figure 4.27: Mainsail head, transversal frequency domain

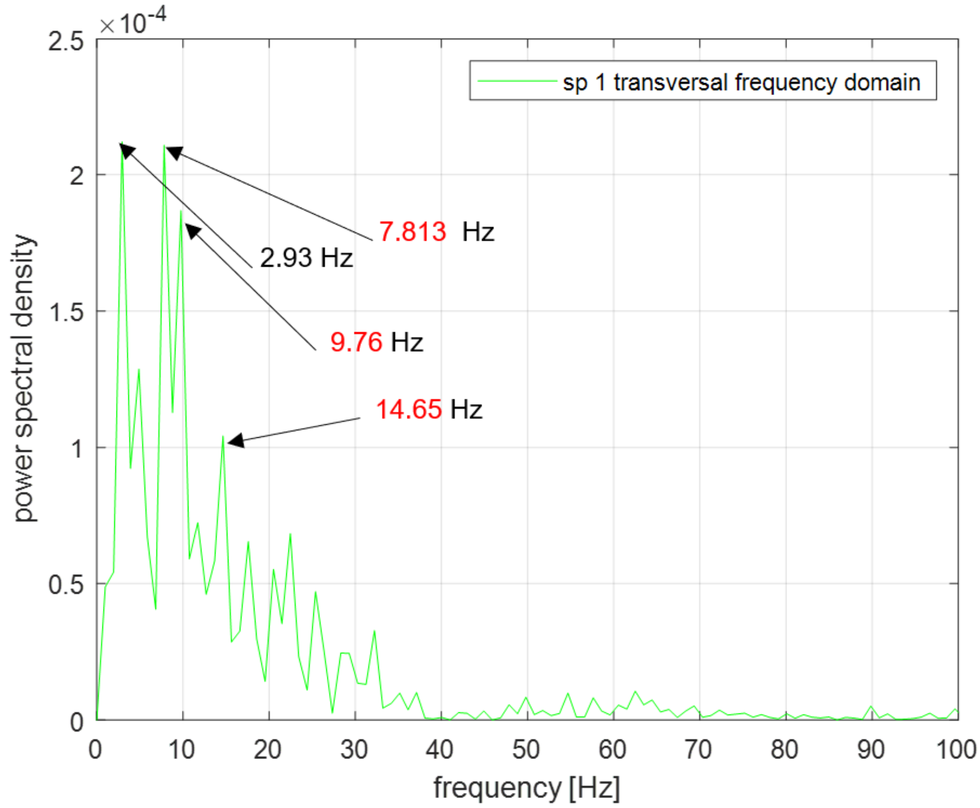


Figure 4.28: Spreader 1, transversal frequency domain

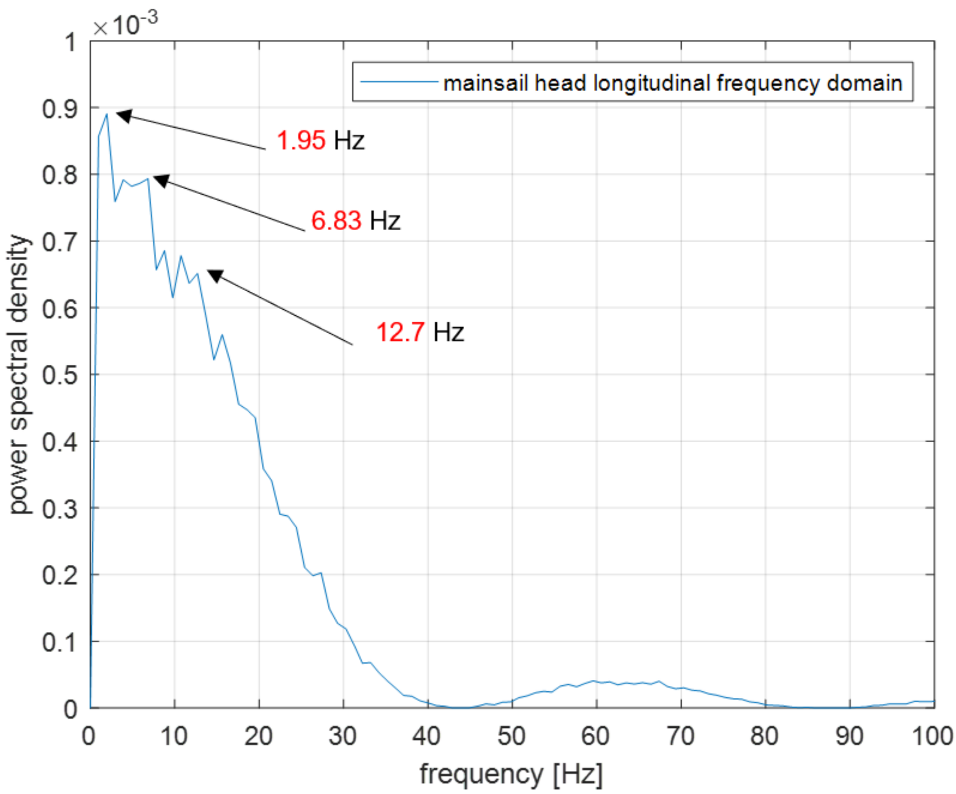


Figure 4.29: Mainsail head, longitudinal frequency domain

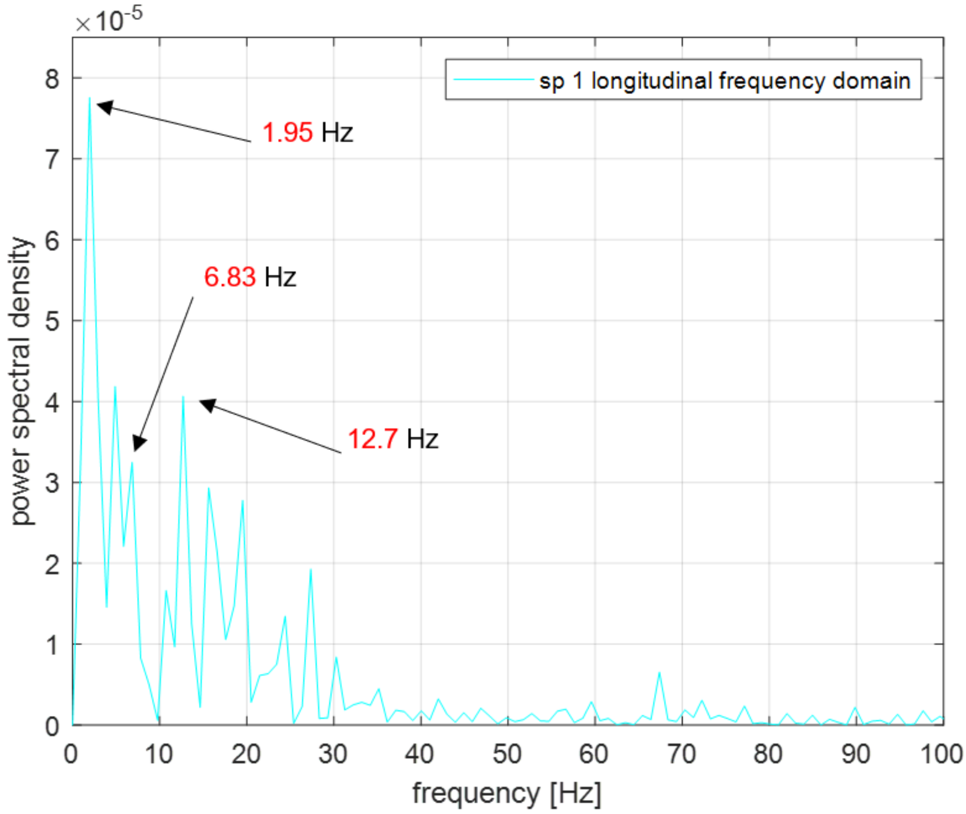


Figure 4.30: Spreader 1, longitudinal frequency domain

5. CONCLUSIONS

The thesis, as presented before, is divided into different. In the first one the design of the mast rig, spreaders and shrouds is performed in order to get the perfect match. Then, with the rig mast configuration adopted, the quasi-static analysis will be carried on to study the behavior of the structure and check stresses, strain and deformations of each part of the rig. As final, the dynamic study of the rig is performed first with a modal analysis and secondly with the application to the structure of the time domain representation of the wind spectrum.

The quasi-static analysis carried on after the dimensioning of the equipment with the DNV guidelines, was performed to check the obtained results. As seen in chapter 4.7, after the analysis, some shrouds of the mast were overloaded, and some diameters need be changed. This fact is not caused by a wrong calculation of the scantling from the DNV guidelines but may be caused by too high wind speed which results in high wind forces applied to the structure. For the analysis what has been found to be overstressed is the condition of the spinnaker and mainsail coupled with the jib, that is the two combinations of sails that expose the biggest area to the wind. Actually, for the increasing of the wind the spinnaker should be dropped, and the area of mainsail and jib decreased by reefing.

Regarding the dynamic analysis, the comparison with the modal analysis provided good results. For the first, second and third mode of longitudinal and transversal direction, the peaks found by the Fourier transformation are almost the same with the values of the natural mode found in the modal analysis. It is possible to notice that for the longitudinal motion the mode that contributes more in the oscillation of the mast rig is the first one. The value of the peak found by the Fourier transformation is *1.95 Hz*, which gives an error of *4.52 %* from the value of the natural mode of *2.03 Hz*. For the transversal motion of the mast tube, the values of the peaks compared with the modal analysis give good results, but a first peak is found, with a frequency of *1.95 Hz* that in the modal analysis is representing the torsional moment oscillating in the transversal plane. This mode was not taken into account before, but with the dynamic analysis it has been noticed to be really influential in the transversal motion. In appendix [G] two images are placed to simulate the motion described.

As future work, I think it will be a good idea to study the dynamic analysis for a longer simulation time in order to reduce the errors between the frequency of the natural mode and the peaks from the Fourier transformation. It is also a good idea to complete this analysis with other combinations of sails and different mean wind speed. Regarding the hull, in order to have a more competitive value of righting moment, it is a good idea to try different shapes of the hull in order to have a better moment opposed to the transversal wind force.

The thesis just took into account the transversal force of the wind. In order to have a more complete study of the problem, it would be a good idea to compare the driving forces of each sail with the resistance of the hull to have a global view of the effective power needed by the yacht and the speed reached for each configuration of sails and wind speed.

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APPENDIX A – HYDROSTATIC REPORT DELFTSHIP

Design hydrostatics report

Design hydrostatics report

Master thesis

Designer	Francesco Mauri
Created by	
Comment	
Filename	Master thesis.fbm

Design length	15.000 (m)	**Midship location**	7.500 (m)
Length over all	15.000 (m)	**Relative water density**	1.0250
Design beam	4.700 (m)	**Mean shell thickness**	0.0000 (m)
Maximum beam	4.693 (m)	**Appendage coefficient**	1.0000
Design draft	2.750 (m)		

Volume properties		Waterplane properties	
Moulded volume	10.146 (m^3)	Length on waterline	14.298 (m)
Total displaced volume	10.146 (m^3)	Beam on waterline	3.319 (m)
Displacement	10.399 (tonnes)	Entrance angle	69.098 (Degr.)
Block coefficient	0.0761	Waterplane area	31.836 (m^2)
Prismatic coefficient	0.5435	Waterplane coefficient	0.6571
Vert. prismatic coefficient	0.1159	Waterplane center of floatation	6.735 (m)
Wetted surface area	45.056 (m^2)	Transverse moment of inertia	20.020 (m^4)
Longitudinal center of buoyancy	6.982 (m)	Longitudinal moment of inertia	338.13 (m^4)
Longitudinal center of buoyancy	-3.625 %		
Vertical center of buoyancy	2.490 (m)		
Total length of submerged body	14.600 (m)		
Total beam of submerged body	3.319 (m)		

Midship properties		Initial stability	
Midship section area	1.279 (m^2)	Transverse metacentric height	4.463 (m)
Midship coefficient	0.1401	Longitudinal metacentric height	35.817 (m)

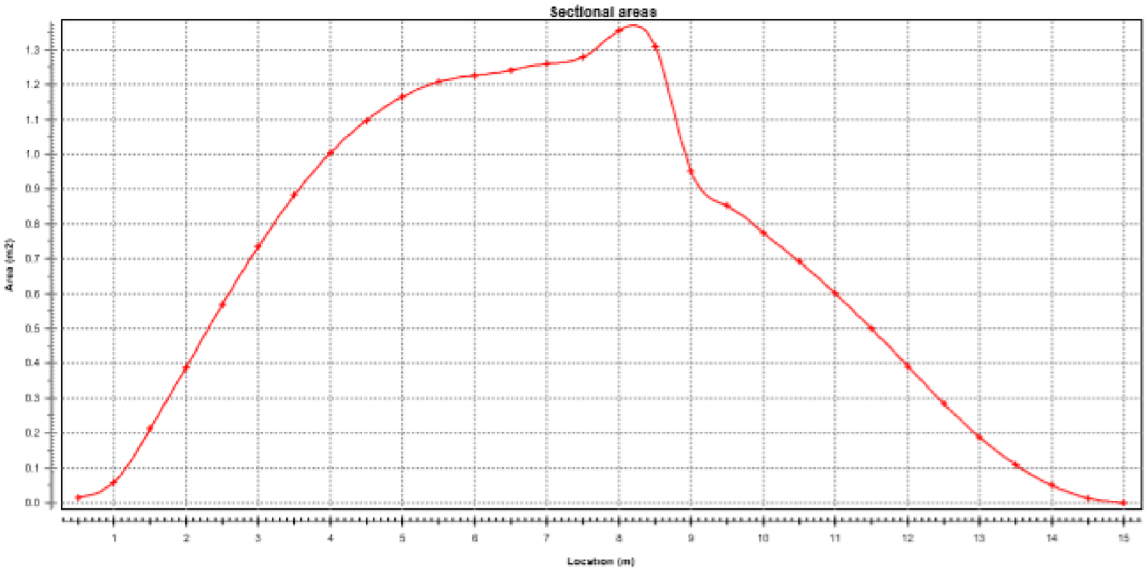
Lateral plane	
Lateral area	9.191 (m^2)
Longitudinal center of effort	7.312 (m)
Vertical center of effort	1.903 (m)

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

Location	Area	Thickness	Weight	LCG	TCG	VCG
	(m^2)	(m)	(tonnes)	(m)	(m)	(m)
hull	82.505	0.001	3.800	7.065	0.000 (CL)	2.982
keel	5.510	0.001	0.900	8.130	0.000 (CL)	1.230
bulb lead	3.168	0.001	3.500	7.793	0.000 (CL)	0.265
rudder	1.469	0.001	0.200	0.650	0.000 (CL)	1.932
deck	45.750	0.001	1.000	5.263	0.000 (CL)	3.869
doghouse	15.474	0.001	1.000	8.209	0.000 (CL)	4.515
Total	**153.876**		**10.400**	**7.215**	**0.000 (CL)**	**2.129**

Sectional areas									
Location (m)	Area (m²)	Location (m)	Area (m²)	Location (m)	Area (m²)	Location (m)	Area (m²)	Location (m)	Area (m²)
0.500	0.015	3.500	0.882	6.500	1.240	9.500	0.852	12.500	0.284
1.000	0.059	4.000	1.004	7.000	1.260	10.000	0.775	13.000	0.188
1.500	0.212	4.500	1.098	7.500	1.279	10.500	0.692	13.500	0.109
2.000	0.389	5.000	1.165	8.000	1.355	11.000	0.600	14.000	0.050

Sectional areas									
Location (m)	Area (m²)	Location (m)	Area (m²)	Location (m)	Area (m²)	Location (m)	Area (m²)	Location (m)	Area (m²)
2.500	0.568	5.500	1.208	8.500	1.310	11.500	0.499	14.500	0.014
3.000	0.735	6.000	1.226	9.000	0.951	12.000	0.392	15.000	0.000



NOTE 1: Draft (and all other vertical heights) is measured from base Z=0.000
NOTE 2: All calculated coefficients based on actual dimensions of submerged body.

Figure A 1: Sectional areas

Hydrostatics

Relative water density : 1.0250

Trim: 0.000 (m)

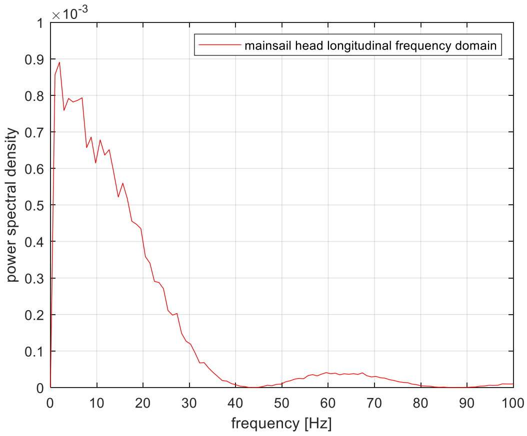
Draft	Displ FW	Displ.	LCB	VCB	TCB	KMt	KMl	MCT	TpCm
(m)	(tonnes)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(t*m/cm)	(t/cm)
2.750	10.146	10.399	6.982	2.490	0.000	4.463	35.82	0.231	0.326

NOTE 1: Draft (and all other vertical heights) is measured from base Z=0.000
NOTE 2: All calculated coefficients based on actual dimensions of submerged body.

Nomenclature

Draft	*Moulded draft, measured from baseline*
Displ FW	*Displacement fresh water*
Displ.	*Displacement*
LCB	*Longitudinal center of buoyancy, measured from the aft perpendicular at X=0.0*
VCB	*Vertical center of buoyancy*
TCB	*Transverse center of buoyancy*
KMt	*Transverse metacentric height*
KMl	*Longitudinal metacentric height*
MCT	*Moment to change trim one unit*
TpCm	*Weight to change the immersion with one unit*

APPENDIX B – LONGITUDINAL FREQUENCY DOMAIN RESPONSE



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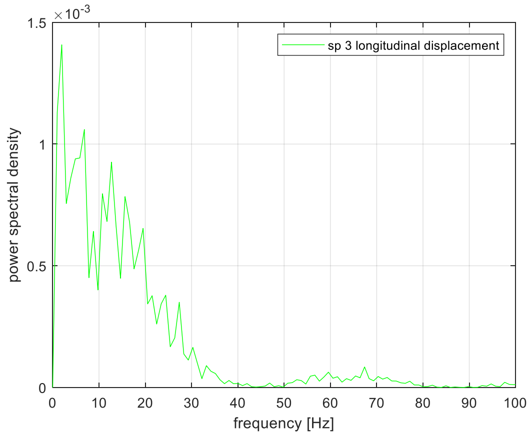

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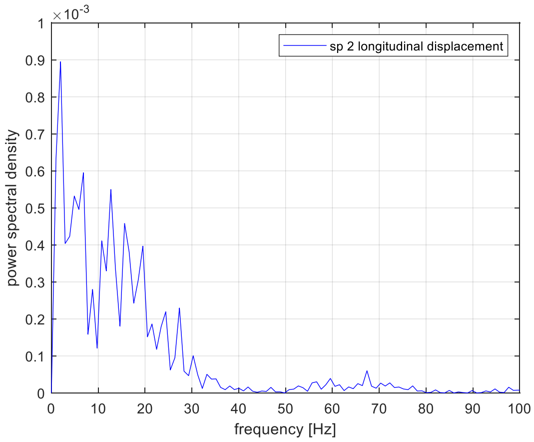

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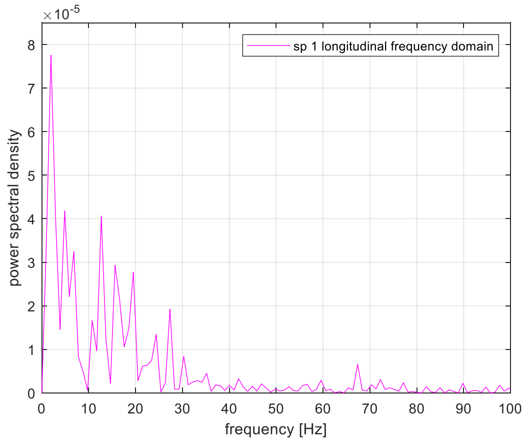

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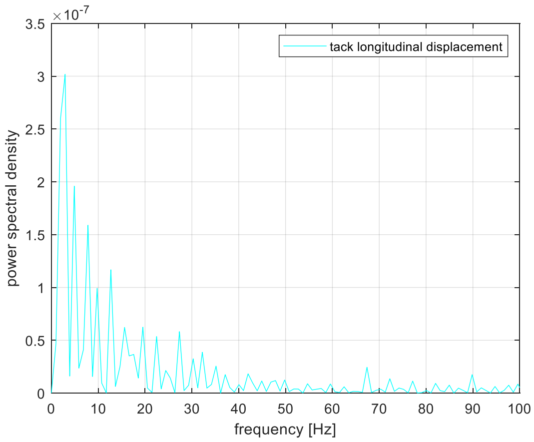
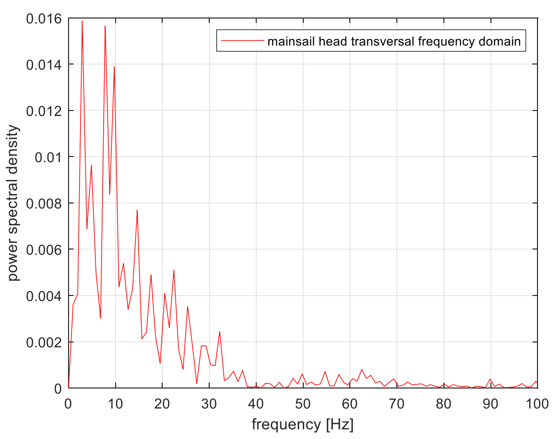


(e)

Figure B 1: Longitudinal frequency domain response

APPENDIX C – TRANSVERSAL FREQUENCY DOMAIN RESPONSE



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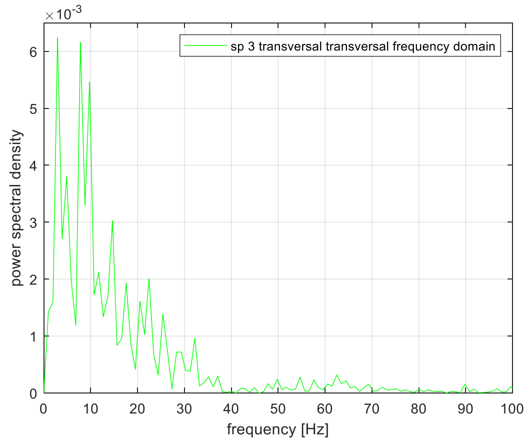

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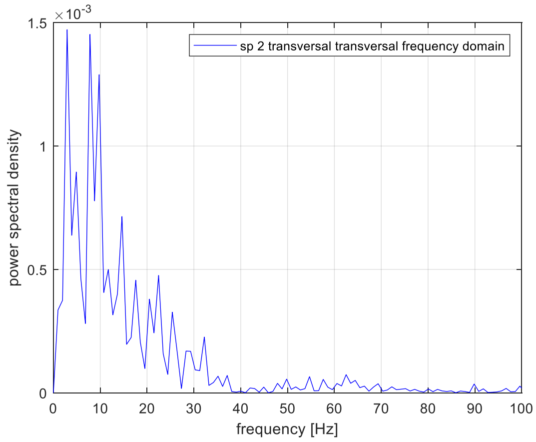

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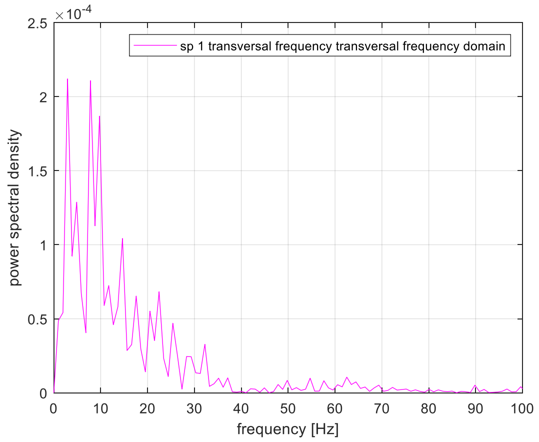

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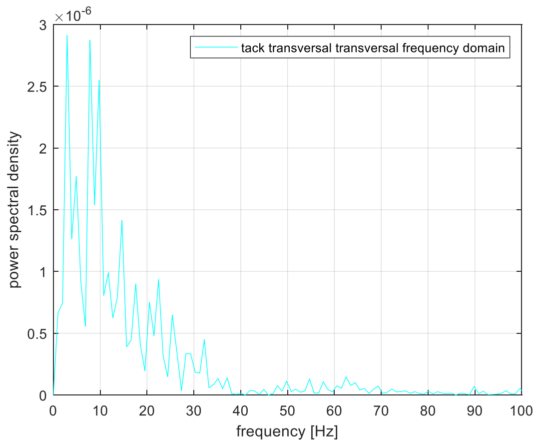

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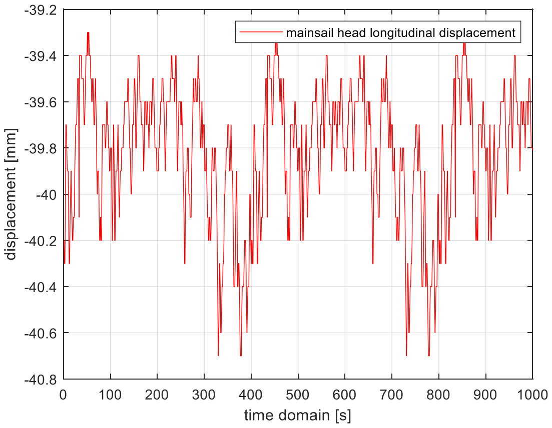
Figure C 1: Transversal frequency domain response

APPENDIX D – LONGITUDINAL DISPLACEMENT OF DYNAMIC ANALISY



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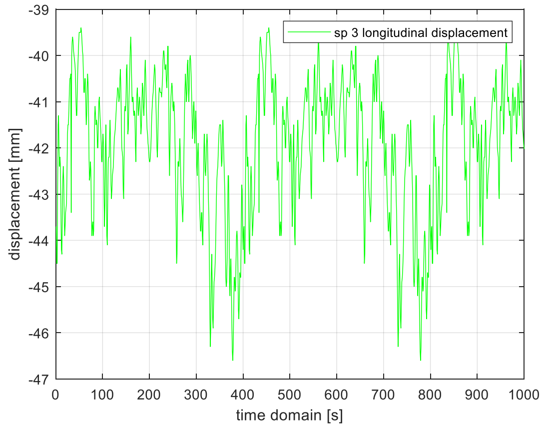

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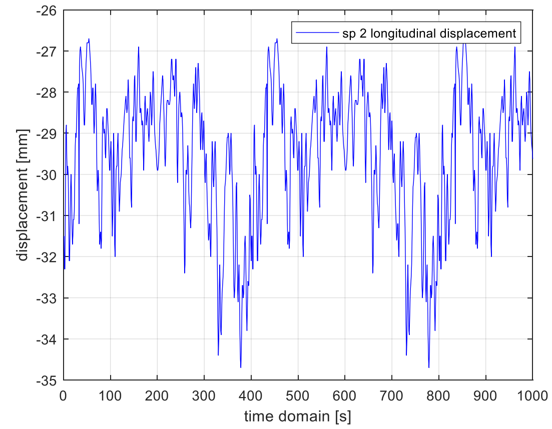

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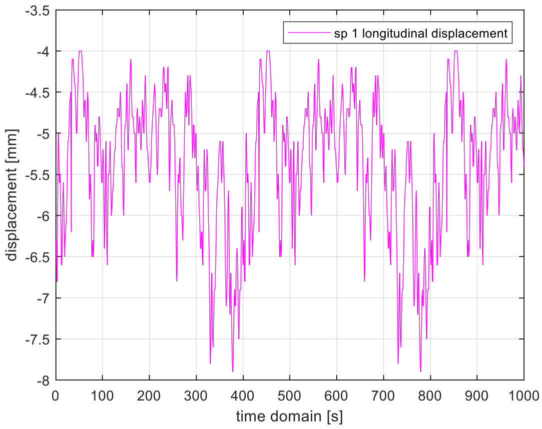

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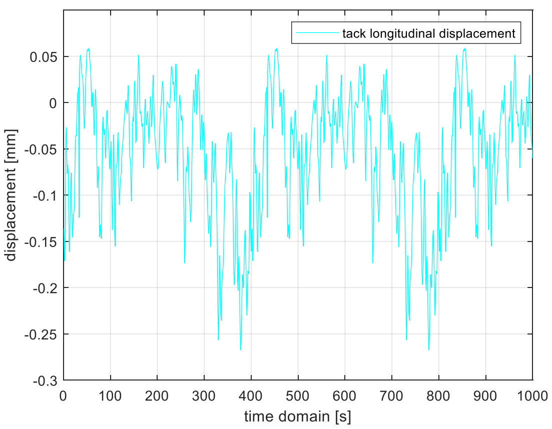
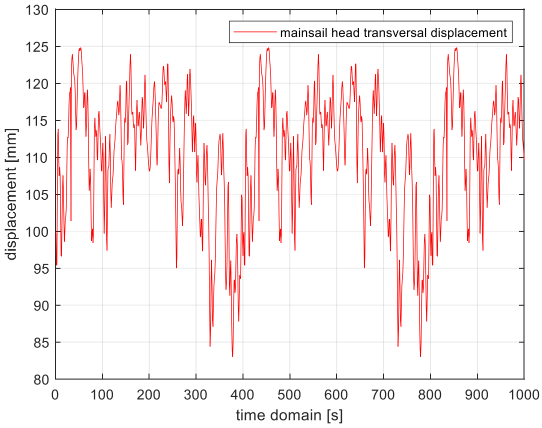


(e)

Figure D 1: Longitudinal displacement of dynamic analysis

APPENDIX E – TRANSVERSAL DISPLACEMENT OF DYNAMIC ANALISY



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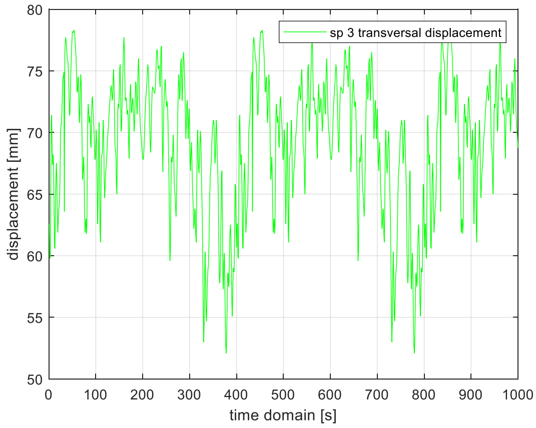

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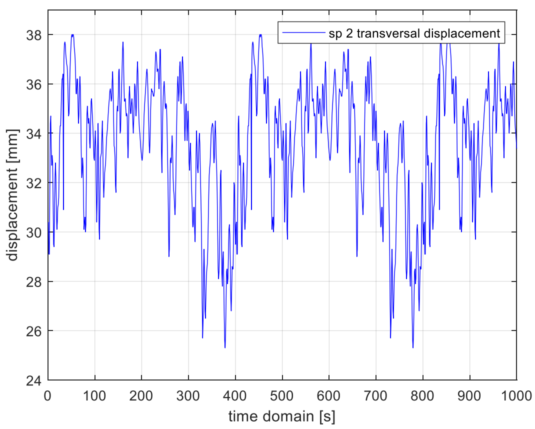

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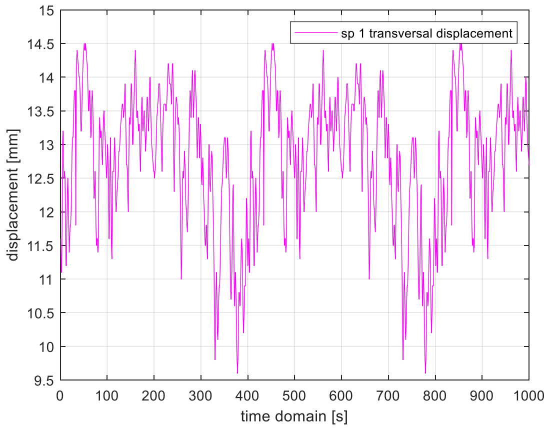

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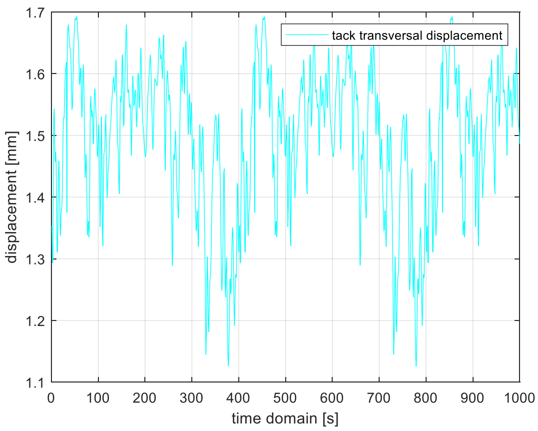

(e)

Figure E 1: Transversal displacement of dynamic analysis

APPENDIX F – TRANSVERSAL DISPLACEMENT OF DYNAMIC ANALISY

Table F 1: Driving and side force for mainsail and jib

Wind speed	2 m/s			4 m/s			6 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)
27	0.49	864.5	245.0	6.87	3424.5	970.4	15.42	7592.4	2151.5
50	0.41	392.7	206.3	3.12	1554.7	816.8	6.91	3447.1	1811.0
80	0.21	154.2	106.3	1.23	613.8	423.0	2.75	1370.8	944.7
100	0.13	69.3	64.6	0.55	276.7	258.0	1.25	621.0	578.9
180	0.05	0.0	23.2	0.00	0.0	92.6	0.00	0.0	208.4
Wind speed	8 m/s			10 m/s					
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)			
27	27.51	12664	3588.9	40.5	16440	4658.9			
50	12.11	6004.3	3154.5	18.5	8777.8	4611.6			
80	4.84	2412.1	1662.3	7.87	3921.0	2702.1			
100	2.21	1099.9	1025.4	3.84	1916.3	1786.4			
180	0.00	0.0	370.4	0.00	0.0	370.4			

Table F 2: Driving and side force for spinnaker

Wind speed	2 m/s			4 m/s			6 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)
80	0.72	260.5	231.5	3.51	1785.8	1125.3	7.75	3934.3	2479.1
100	0.17	0.0	54.3	2.87	1033.4	918.6	6.37	2294.1	2039.2
180	1.77	956.5	565.5	0.68	0.0	217.1	1.53	0.0	488.4

Wind speed	8 m/s			10 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)
80	13.5	6792.7	4280.3	22.3	9998.8	6300.6
100	11.2	4002.9	3558.1	17.6	6694.6	5950.7
180	2.7	0.0	868.3	1.80	0.0	868.3

Table F 3: Driving and side force for mainsail

Wind speed	2 m/s			4 m/s			6 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)
27	0.93	436.5	123.1	3.70	1738.7	490.4	8.27	3884.7	1095.6
50	0.59	277.5	187.6	2.35	1102.4	745.3	5.22	2453.1	1658.5
80	0.27	126.1	84.1	1.07	502.4	335.0	2.39	1123.1	748.8
100	0.14	66.9	68.7	0.57	267.0	274.3	1.28	599.2	615.6
180	0.00	0.0	21.7	0.00	0.0	86.8	0.00	0.0	195.3

Wind speed	8 m/s			10 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)	Cond. Eq. (°)	A_{Side} (N)	$A_{Driving}$ (N)
27	14.70	6837.7	1928.4	21.8	9802.9	2764.7
50	9.15	4294.9	2903.7	13.8	6458.1	4366.2
80	4.21	1978.9	1319.4	6.86	3222.7	2148.8
100	2.26	1061.3	1090.3	3.94	1848.7	1899.1
180	0.00	0.0	347.1	0.00	0.0	347.1

Table F 4: Driving and side force for jib

Wind speed	2 m/s			4 m/s			6 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A Side (N)	A Driving (N)	Cond. Eq. (°)	A Side (N)	A Driving (N)	Cond. Eq. (°)	A Side (N)	A Driving (N)
27	0.95	502.6	141.8	3.77	2001.8	564.6	8.42	4472.0	1261.2
50	0.29	153.3	32.9	1.15	611.2	131.2	2.57	1367.8	293.5
80	0.08	41.5	31.4	0.31	165.8	125.3	0.70	372.4	281.5
100	0.05	24.9	23.7	0.19	99.4	94.6	0.42	223.6	212.7
180	0.00	0.0	15.2	0.00	0.0	60.8	0.00	0.0	136.8

Wind speed	8 m/s			10 m/s		
Apparent wind angle (°)	Cond. Eq. (°)	A Side (N)	A Driving (N)	Cond. Eq. (°)	A Side (N)	A Driving (N)
27	15.0	7870.1	2219.6	22.2	11264.	3176.9
50	4.5	2413.3	517.9	6.89	3660.9	785.6
80	1.2	660.3	499.1	2.04	1085.0	820.1
100	0.7	396.9	377.6	1.31	694.6	660.7
180	0.0	0.0	243.2	0.00	0.0	243.2

APPENDIX G – TORSIONAL AND TRANSVERSAL MODE OF MAST MOTION

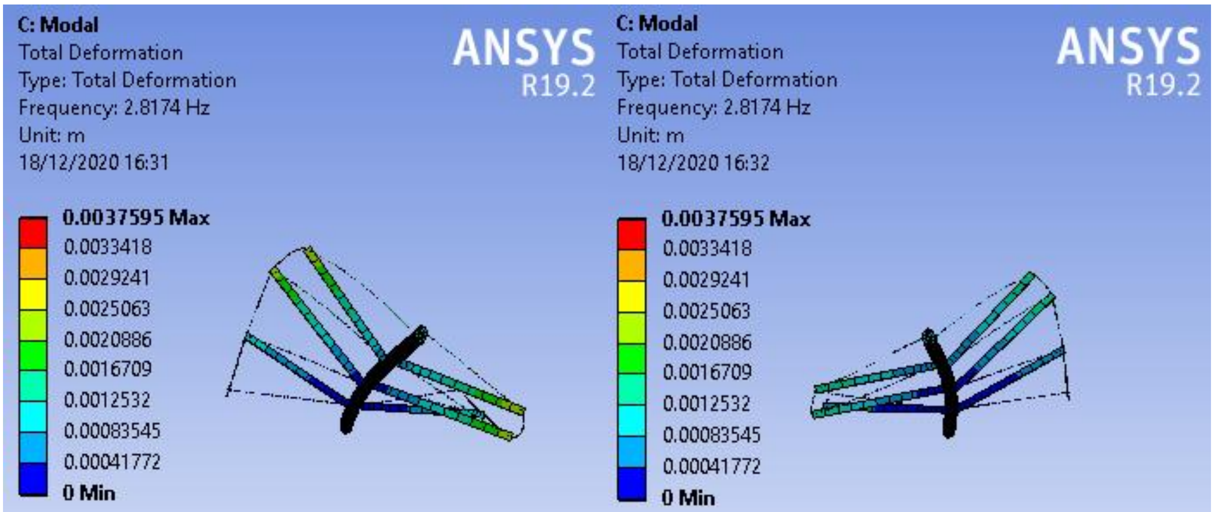

Figure G 1: Torsional motion of the mast tube