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

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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 behaviour 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 analysed 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.

1. Introduction

The great distribution of sailing for amateurs leads an even increasing number of fans of getting in touch and being interested by the word of the sailing yacht. Not only for recreational reasons but also for the interesting physics that drives a yacht in the ocean with the only force of the wind, which is the reason why I consider this thesis really 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 sailboats. In the software small variation of the hull and the weight distribution of its components are performed. After this part is concluded, the static and hydrodynamic properties are studied [1]; the knowledge of the use of the software *Archimedes will be useful*, which will perform the static analysis of the hull [2]. For each angle of tilt, the software will return the heeling moment that the hull needs to get the angle of the heel. So, this part is the basis to perform the design and dimensioning of the entire rig [3], because according to the reference [4], the rig will be designed for the static righting moment of the yacht at full displacement with a heel angle of 30° [5]. 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 [6].

After this part is done, the quasi-static analysis will be carried on [7]. 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 [8]. Now, the wind speed is the beginning of this study. With the *G. Hazen* model of the reference [9], for different wind speed and apparent wind angle what are computed are the side and driving force generated on the three different types of sails considered: 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 behaviour.

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 [4, 10]. 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 be converted, 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 [11].

The thesis is divided into different parts and each one has different objectives. First, the design of the mast rig, spreaders and shrouds will be performed [12], different configuration sails will be analysed in order to get the perfect match for the rig to support wind loads for the type of yacht considered [13]. Then, with the rig mast configuration adopted, the quasi-static analysis will carry on to study the behaviour 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 the 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.

2. Methodology

2.1.Physics of a sailboat

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) [14].

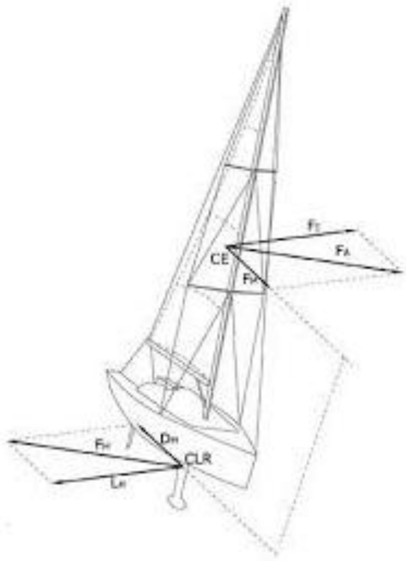

Figure 2. 1: Principle of equilibrium between aero and hydro forces

The fundamental requirement of any boat is the buoyancy and this force came out with the *Archimedes theory.* This equation allows 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 if external forces are applied that may generate a torque.

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

To carry out the study of the rig system, it is fundamental to be aware of the stability of the sailboat. 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.

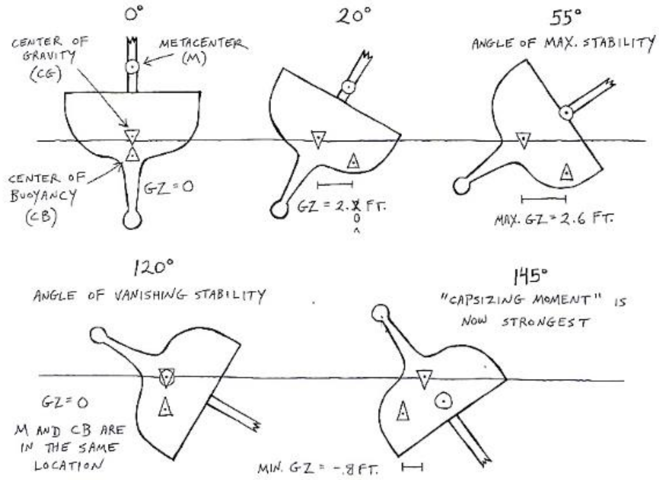

Figure 2. 2: Stability of a sailboat

As the sailboat is heeled by an external force, i.e. wind force, the hull generates an opposing moment that contrasts the external force of the wind to the rotation of the hull.

2.2.Sail plan

The start of the project of the propulsive plan can be schematized as follows:

- Determination of the sail area of reference SAR;
- Choice of thee 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). Once decided the sail area of reference and chosen the type of equipment (sloop: one mast), it occurs 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. For the type of study the sails adopted are: mainsail, jib and a spinnaker.

2.3.Scantling of the equipment

Chosen the type of sails and the equipment, now it occurs to dimension the equipment. The main parts that are subjected to the dimensioning are: mast, shrouds, stays and spreaders [15].

The calculations of the rig scantling follows the guideline of Germanischer Lloyd: "Guideline for Design and Construct of Large Modern Yacht Rigs". The study of the rig has to be performed on the basis of the stability of the sailboat, and can be divided in the determination of rig loads (on standing and running rig) and the dimensioning.

The transverse forces on the sails are determined by the righting moment of the sailboat. According to this guideline, each sail's contribution to the resultant heeling moment is assumed to be proportional to the sail's area and the distance of its centre of effort above the underwater body's centre of lateral resistance, the position of each barycentre, as seen in Figure 2.3.

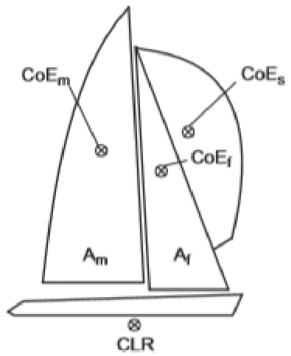

Figure 2. 3: Barycentre of each sail and hull

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.

The configurations of sails taken into account are: mainsail coupled with jib, mainsail and jib only and spinnaker. After have obtained the five forces acting on the sailboat, the force of each shrouds is calculated analytically knowing a priori the configuration of the shrouds, the spreaders and the length of each panels of the mast. The configuration of the rig is set down to have a sweep of the spreaders of 20°, a constant division between the four panels of the mast of 20.70 meters. The spreaders are divided in four diagonals (d) and three verticals (v).

From the sails to the hull, the transversal wind force is redistributed as sketch in the Figure 2.4.

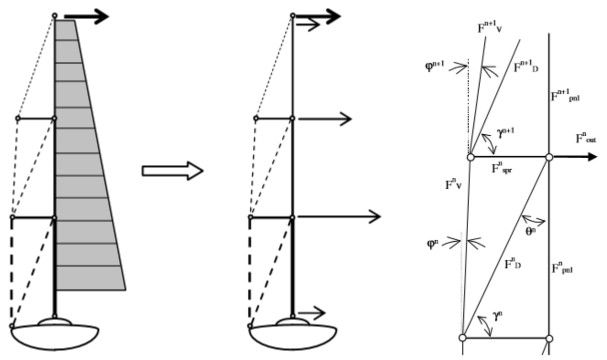

Figure 2. 4: Distribution of the forces on the rig

The dimensioning of the shrouds is done according to the ultimate break load specified valid for Nitronic 50 Rod rigging.

For the mast dimensioning, the method adopted is present in reference Principle of Yacht Design [16]. The mast has to contrast two different stresses that is 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 and longitudinal inertia I_y, the formulation is given and the value is multiplied by 1.5 to handle dynamics factors.

2.4.Practical model for sail and rig aerodynamics

In the second part of the study the transversal sail force is not given by the righting moment of the hull but directly by the wind acting of the sails [17]. The model used for the aerodynamics of sails of the yacht was presented in 1980 by G. Hazen, in the Hazen's model the lift and viscous drag of each sail are described as functions of the apparent wind angle [18]. The coefficients are given for these apparent wind angles: 27°, 50°, 80°, 100°, 180° and the coefficients are given for five sails: main sail, jib, spinnaker, mizzen sail, mizzen stays.

With the model for each wind speed chosen and each apparent wind angle, for the sails considered it is possible to find side and drive force. This study will be useful for later analysis.

2.5.Modal analysis

The modal analysis is the dynamic study to provide information about the structure's dynamic behaviour when the structure is vibrating. This analysis is really important for our case because the dynamic responses analysis of the mask 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 lately a spectrum analysis is performed. For the complexity of the structure, the analysis is carried out with the software *Ansys* [19]. 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.

2.6.Wind spectrum

The generation of the wind spectrum is done according to the reference [4], which proposes various types of spectrum idealization. According to the type of study carried on and on reference [20], the Kaimal spectrum is adopted for the wind representation.

In the reference [4] two main components of the wind speed are found: the stationary component, which is characterized by few changes and a turbulent component, which is characterized by high frequencies of changes. It is exactly this component that may induce quick and unpredictable behaviour in the structure.

The *Kaimal* spectrum used describes 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.

3. Case of study

3.1.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 3. 1.

Figure 3. 1: DELFTShip model of the simulation

Slight adjustments are done on the shape of the yacht, the consistent part was the definition of the weight of the various section of the yacht, basing almost on similar yachts with the same dimensions and aims. The main parts of the yacht hull are: hull, keel, bulb lead, rudder, deck and doghouse. The main dimensions of the model are reported in Table 3.1.

Table 3. 1: Main dimensions

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

As final computation the hydrostatic characteristics are found whose the main aim is to know the position of the centre of gravity and buoyancy required later. Values are in Table 3.2.

Table 3. 2: Position of LCB, VCB and LCG, VBG.

Part	LC (m)	VC (m)	TC (m)
Hull (weight)	7.065	2.982	0.0
Hull (hydrodynamic)	6.982	2.690	0.0

3.2.Stability of the sailboat

For the calculation of the righting moment of the yacht, the software *Archimedes* is used whose main scope is to define the displacement of the centre of buoyancy caused by transversal inclinations compared to its position of the uninclined yacht.

Figure 3.2 reports the righting moment of the yacht.

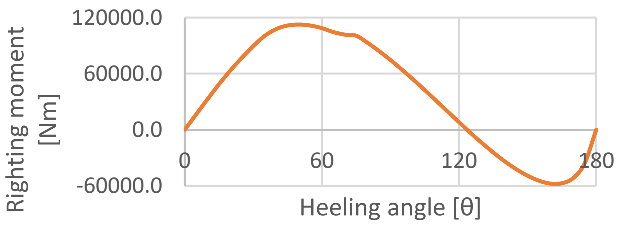

Figure 3. 2: Stability graph of the sailboat

3.3.Drawing of the sail plan and mast configuration

After having found an idea of the value of the SAR, it is important to choose the type of equipment and define the entire sail plan, and after this step it is possible with the stability of the sailboat to compute the quasi-static analysis.

The yacht is designed to be sloop with the mast of 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 3.3 all the final values of the sail plan configuration are placed.

Table 3. 3: Mast and sail plan configuration

Sail plan division					
SAR	127.7	(m^2)			
P	19.7	(m)	I	20.7	(m)
E	5.5	(m)	J	7	(m)
P/E	3.6	(-)	I/J	2.96	(-)

With the height of the mast of 20.7 meters it is decided to divide it into four panels of equal length of 5.175 meters. This choice is done in order not to have a too long distance between the spreaders to avoid possible buckling. Fixed the number of panels three are the spreaders for each side of the mast used. Each spreader has an angle of attack of 20°.

3.4.Mechanical proportion of the equipment

The mechanical proportional of the equipment is done with four different combinations of sails: mainsail coupled with jib, only the main sail, only the jib and the spinnaker. In Table 3.4 the main data used to get the transverse forces and its distribution on the mast for the four different cases are presented.

Table 3. 4: Main data for the transversal force

$RM_{(\text{Heeling angle } 30°)}$	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	(-)

The determination of the working load, so the actual axial stress of each part of the rig is computed analytically for the four conditions decomposing geometrically the transversal forces calculated before on each part. For the later dimensioning each tension is multiplied by a reserve factor, suggested to be ≥ 2.5 from the guideline.

Knowing the values of the maximum axial forces it is possible to get the diameter of each part. The material that is used for the shrouds is Nitronic 50. Its main proprieties are reported in Table 3.5.

Table 3. 5: Nitronic 50 properties

Nitronic 50		
Density	7880	(kg/m^3)
Ultimate	730	(N/mm^2)
Tensile	420	(N/mm^2)
Elongation	35	(%)
Reduction of area	55	(%)

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

Regarding the mast proportion, after knowing the transversal and longitudinal inertia required, the mast properties are chosen following the example for the mast profiles and characteristics presented in the Principle of Yacht Design. In the reference [9], entering with the required minimum interties, the mast section and wall thickness are obtained. Final values are shown in Table 3.6.

Table 3. 6: Mast final properties

Length (mm)	Breadth (mm)	I_y (cm^4)	I_x (cm^4)	Wall thick. (mm)	Weight (kg/m)
274	185	3650	1650	4.9	10.32

For the material used, aluminium alloy is used for both the mast and the spreaders. The proprieties of the aluminium are shown in Table 3.7.

Table 3. 7: Aluminium physical properties

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

3.5.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 reason. According to the reference, the pretension has to be set in order to have tension also in the leeward side when sailing at heeling angles at or below the "SWA".

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. The condition, which is done the 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 shrouds and stays. The forces are applied in six different points. The force of the mainsail is divided between tack (F), spreader 1 (G), spreader 2 (H), spreader 3 (I), mainsail 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 3.3 shows clearly this.

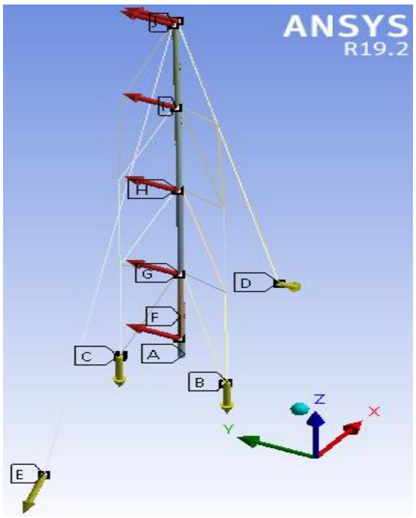

Figure 3. 3: Pretension rig sketch of forces and displacement

3.6.Quasi-static analysis

The main idea of the quasi-static analysis is to get the maximum stresses possible in the structure and the study of its behaviour [21, 22]. The forces applied are directly derived from the G. Hazen model. The force of the wind is calculated for different wind speeds and different apparent wind angles. For the quasi-static analysis, two different types of simulations are done. The first one is done fixing the wind speed at *10 m/s* and changing the apparent wind angle. The angle is changed according to complete a jibe and a taking, the two main manoeuvres in order to change the side of the force. The apparent angle of the wind is made to change from $27°$ to $-27°$, passing from $180°$ (with a jibe), and from $-27°$ to $27°$ (with a tacking). This is applied just on the mainsail and jib. For its nature, for the spinnaker the angle is varied from $80°$ to $-80°$, completing just a jibe. It is impossible to do a tacking with this type of sail.

After the first analysis the worst apparent wind angle is found, and the second analysis is run out fixing that angle for each condition and increasing and decreasing the wind speed from *2* m/s to *10 m/s*.

A quasi-static analysis is considered because for both the wind speed and apparent wind angle the values are changed 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.

With the first simulation it has been found out that some shrouds were overstressed and an increase of the diameters has to be done. The change of the diameters is a complex process. Every time the diameters of the components overstressed are varied the rig behaves differently because the stresses and deformation are redistributing 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 out 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 final values in the end of this computation are reported in Table 3.8.

Table 3. 8: Diameters adopted

Components on upwind side	Yield strength (N/mm²)	% of stress (-)	Second diameters (mm)	First diameters (mm)
Dn_3	259.6	61.8%	7	7
Vn_2	265.8	63.3%	6.75	6.75
Dn_2	268.0	63.8%	8	6.2
Vn_1	348.6	83.0%	9	9
Dn_1	358.1	85.2%	10.8	6.65
Vn	347.9	82.8%	13.5	10.7
Dn	292.1	69.5%	11.5	8.45
Fore stay	214.9	51.2%	20.4	20.4
Back stay	214.7	51.1%	17.3	17.3

3.7.Dynamic analysis

After the quasi-static study of the structure a dynamic analysis is performed. First the three natural frequencies of the structure are found with a modal analysis and later the wind speed is schematized as a spectrum in time domain and applied to the structure.

Modal analysis

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

This type of study performed will be really 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 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 3.9.

Table 3. 9: Global natural mode of the rig

Natural mode			
First mode longitudinal [Hz]	2.04	First mode transversal [Hz]	7.64
Second mode longitudinal [Hz]	6.88	Second mode transversal [Hz]	9.86
Third mode longitudinal [Hz]	11.2	Third mode transversal [Hz]	14.9

Wind spectra generation

In the reference [4], 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*.

With the equation given for the Kaimal spectrum, and using as input values that want to characterize the study carried on, it is possible to obtain the spectral density energy in function of the frequency range used. Figure 3.4 shows the result.

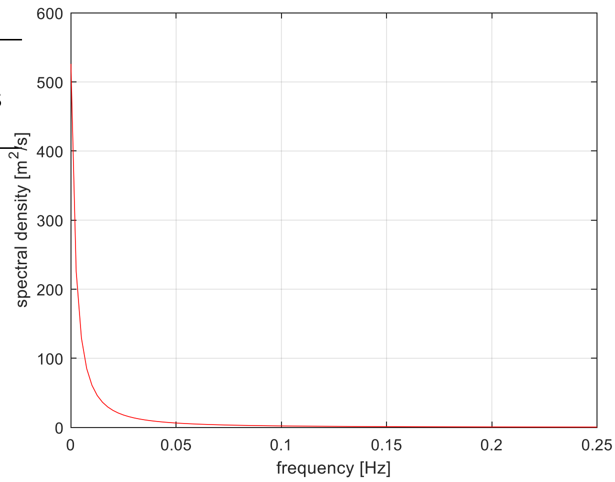

Figure 3. 4: Kaimal spectrum generation

To obtain the time domain wind speed the turbulent wind speed $v_t(t)$ is calculated with two simple transformations. Figure 3.5 is the result of the transformation for a time domain resolution of *1000 s*. The mean speed of the wind considered for the simulation is *9 m/s*, considered a good value for reaching gusts not over the 11 *m/s*, speed considered maximum value for the characteristic and type of sails considered.

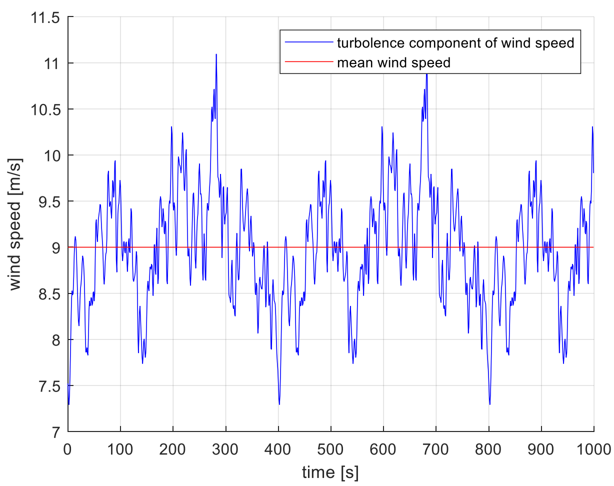

Figure 3. 5: Time domain wind speed

Wind spectral analysis

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

1. First step: the generation of the wind spectrum
2. Second step: the generation of the time domain from the wind spectrum

3. Third step: calculation of the forces, following G. Hazen model reference [9], generated by the wind on the mainsail and the jib for each *dt = 1s*. Repartition of the forces from the barycentre of the two sails on the rig from: mainsail head, jib head, sp. 3, sp. 2, sp. 1 and tack.
4. 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 carried out for *1000 s*.
5. Final step: the generation of the Fourier transformation to get the frequency response of the system and comparison with the modal analysis.

In the Figure 3.6, a sample of the mainsail head displacement for the *X* in the plane *X0Y* is given.

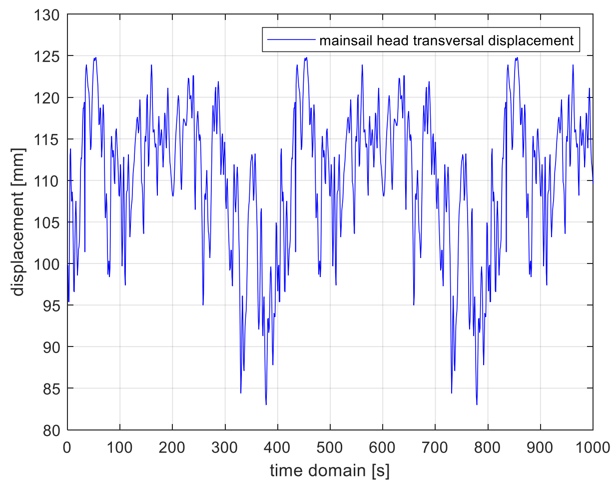

Figure 3. 6: Mainsail head transversal displacement

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. All the five points of the rig for longitudinal and transversal displacement give the same frequency for each peaks. It is different the amplitude of the frequency 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 3.7-3.8 an example is given for the longitudinal and transversal motion in the frequency domain found.

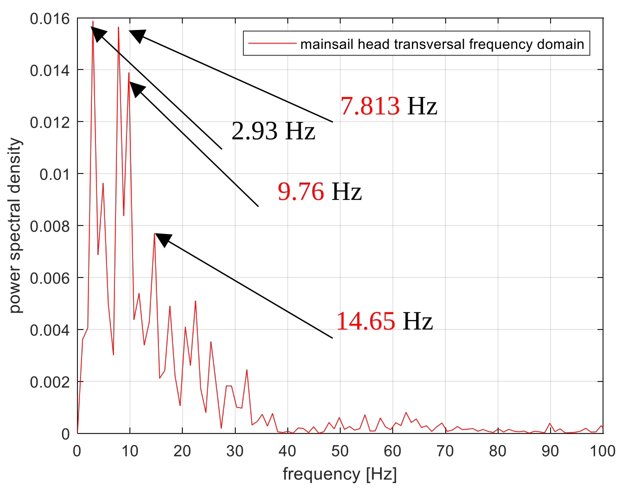

Figure 3. 7: Mainsail head, transversal frequency domain

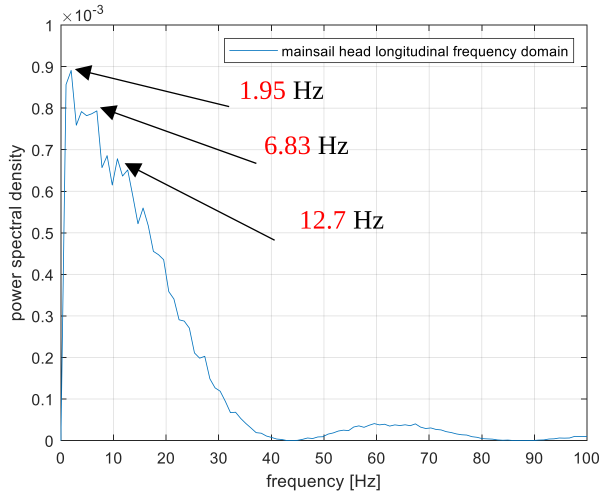

Figure 3. 8: Mainsail head, longitudinal frequency domain

4. Conclusion

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 behaviour 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, which 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.

Figure 4.1-4.2 wants to show the combination of the torsional and transversal motion of this mode.

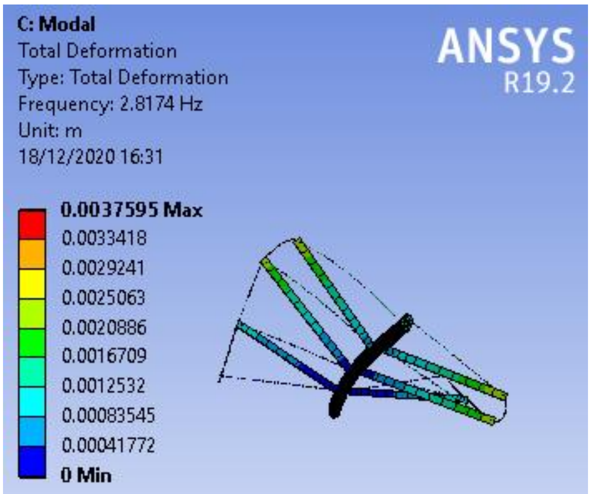

Figure 4. 1: Torsional motion of the mast tube, first position

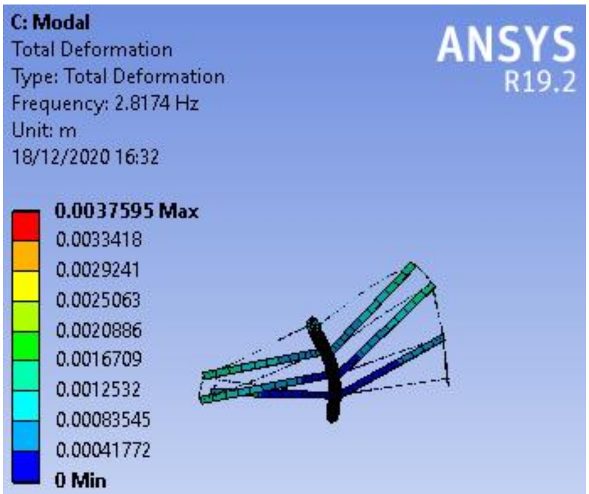

Figure 4. 2: Torsional motion of the mast tube, second position

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.

References

[1] Siroli G., Stecchi A. (february 2010). Physics of sailboat, pp. 70–79.

[2] LauMar (March 2018). Assetto dinamico e statico di una imbarcazione. Yatch&Vela, https://www.yachtevela.com/assetto-dinamico-e-statico-di-una-barca-conoscerli-serve-3230.html.

[3] Janssen R. (2004). Best Mast: a new way to design a rig. Amsterdam: International symposium on “yacht design and yacht construction”.

[4] DNV-RP-C205 (October 2010). Enviromental Condition and Enviromental Loads. Oslo: Det Norske Veritas.

[5] Germanischer Lloyd Aktiengesellschaft (July 2009). Guidelines for Design and Construction of Large Modern Yatch Rigs. Volume I, Part 4. Harmburg: Germanischer Lloyd Aktiengesellschaft.

[6] Boote D., Shenoi, A. (2009). Sailing yacht Design, 17th INTERNATIONAL SHIP AND OFFSHORE STRUCTURES CONGRESS 16-21 AUGUST 2009 SEOUL, KOREA

[7] Grabe, G. (2004). The Rig of the “UCA” – Finite Element Analysis. Amsterdam: The 18th International Symposium on “Yacht Design and Yacht Construction”.

[8] Jerman B. (2010). The Local Buckling of the Thin Walled Aluminium Mast. Ljubljana: University of Ljubljana, Faculty of Mechanical Engineering

[9] Larson L., Eliasson R. (2000). Principles of Yacht Design. II edition, London: Adlard Coles Nautical.

[10] Branlard E. (February 2010). Generation of time series from a spectrum: Generation of Wind times series from the Kaimal spectrum, Generation of wave times series from the JONSWAP spectrum. Denmark: Technical University of Denmark, DTU.

[11] Van der Male P., Eliz-Mari L. (February 2015). Operational Vibrating-Based Response Estimation for Offshore Wind Lattie Structure. In book: Structural Health Monitoring and Damage Detection, Volume 7, pp. 83-93, Chapter 9.

[12] DNV-GL-ST-0412 (2016). Design and construction of large modern yacht rigs. Section 1. Oslo: Det Norske Veritas.

[13] Janssen R.J (2001). Comparison of different rig configurations for an Open 60. Delft: Delft university of Technology.

[14] Claughton (1998). Sailing yacht design: theory. Harlow: Addison Wesley Longman Limited.

[15] Ploé P. (2012). Scantling of sailing yacht mast and sail deformation simulation using Finite Elements. La Spezia: University of Genoa.

[16] Crepaz S. (1986). Teoria e progetto di imbarcazioni a vela. I edition, Milano: Nicola Zanichelli editore.

[17] Bak S., Yoo J., Yong Song C. (2013). Fluid-structure interaction analysis of deformation of sail of 30-foot yacht. Korea: Mokpo National University.

[18] Abbott I.H., Doenhoff A.E.V. (1949). Theory of wing sections. New York: Dover Publications.

[19] ANSYS Inc. (2009). ANSYS 19.0 User Manual. ANSYS Inc.

[20] Fabio C. (2010). Metodologie di controllo avanzate per aerogeneratori off-shore. Milano: Politecnico di Milano, Facoltà di Ingegneria dell’Informazione, Corso di Laurea Specialistica in Ingegneria dell’Automazione.

[21] Jatulis D., Kamaitis, Z. and Juozapaitis A. (2007). Static behaviour analysis of masts with combined guys. Journal of Civil Engineering and Management, Vol. 13, No. 3, pp. 177-182, 2007.

[22] Enlund H., Pramila A., Johansson P. G. (1984). Calculated and measured stress resultants in the mast and rigging of a Baltic 39 type yacht. London: Proceedings of the International Conference on Design Considerations for Small Craft, pp. 320-332.