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Analysis of the Behavior of Moored Ships When Submitted to the Wind Force

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Abstract
Mooring is a common operation carried out by ships when they are moored in ports. With the growth of the ship's main dimensions and the growth of their sail area, the external forces that are supported by the mooring is also growing. To ensure that a ship will support a given wind, the responsible for the mooring, in some cases, uses too many hawsers. This attitude implies in an overuse of resources and time. It is possible, using methods that integrate the mechanical mooring problem, to calculate the maximum wind speed a given mooring configuration can withstand. The present paper demonstrates a method for calculating this speed. After the presentation of this method an analysis is done, using one vessel and one pier, both theoretical. This analysis, made through calculation with the method, observes the influence of the transversal hawsers on the maximum wind speed supported by the ship. The results show that it is possible to increase wind resistance by up to 44% with the proposed modifications. It is concluded that there are other ways to increase wind resistance without adding extra hawsers to the ship.

1 - Introduction

Shipping is an activity that regulates many other activities in maritme environment. Shipbuilding is one of them. A growing demand for transportation will also implies in a growing demand for new ship's construction. And the ship's design also changes according to demand.

This demand for increased transport means, in many cases, increasing the size of vessels, to allow the same vessel to carry more merchandise or passengers. When the length of a ship increases, its surface exposed to the wind will be larger and this will cause a more relevant wind force to be considered during the ship design.

When speaking of the forces acting on a moored ship, the wind force is one of the most important. Another important force are the forces related to currents, waves and tide. In any case, the sum of the external efforts on the ship causes a displacement and rotation on it. Since the ship is moored, a loading or unloading operation may be ongoing and such movements may interrupt those ongoing operations. For this reason, the hawsers make a connection between the ship and the pier so that the vessel can withstand external forces and have as little movement as possible. In this sense, it is possible to understand that if more hawsers are used, the ship will move less.

On the other hand, each hawser added to a ship increases the cost of construction as well as the operational time. Indeed, in addition to the hawser itself, the shipowner will have to pay the costs of other equipment, such as the winch, which are necessary to get another hawser. Another negative point in adding hawsers is that this increases the time of the mooring operation for the ship. In any case, it is understood that the increase of hawsers creates a higher cost for the ship-owner.

So, it is important that the shipyard, responsible for the construction of the ship, knows how to define an optimal configuration, which is the number of hawser and their position on the ship. And, in this way, minimize the costs of the ship to the shipowner, while remaining competitive in the market.

In addition to minimizing costs, the shipyard needs to ensure that the ship will be able to withstand external stresses in given mooring situations with the defined configuration.

2 - Mooring equipment's

The mooring is an operation performed when a ship stops on a pier. The main purpose of this operation is to ensure that the ship does not move away from the pier or rotate on it when subjected to the external forces being applied on this vessel.

There are some elements involved on this operation. The elements that are part of the vessels are usually called mooring equipment. The main ones are listed below.

Hawser or Cable: Line connecting the ship to the pier. It is manufactured in different types of materials. In general, composite material such as nylon, polypropylene and Dyneema. Steel cables that was used in the past are actually becoming an occasional solution due to the difficulty of the operation created by the heaviness of this material.

Winch: Equipment where the hawser is rolled and stored. It is considered as the starting point of the hawser for calculation purposes. It also serves to recall the hawser or provide a tension on it.

Double Bollard: Fixed and resistant equipment where the hawser can be fixed. For calculation purposes, it is considered as a winch, however it cannot generate a tension on the hawser.

Roller: Equipment where the hawser will pass if a change of trajectory is required. In general, they are placed to ensure that the same winch can send a hawser for different fairleads.

Fairlead: Equipment where the hawser passes before leaving the ship. It looks like a hole in the hull of the ship. There are two different types of fairlead. The roller fairlead and the Panama fairlead. The difference between them is the shear stress generated between the fairlead and the hawser, considered small, or negligible, for the roller fairlead.

There are two other elements that are used during mooring operation but are part of the pier.

Bollard: Fixed and resistant elements where the hawser will be fixed. For the calculating purposes, it is considered the last point of the hawser.

Fender: Large elements that prevent the ship from colliding directly with the pier. During the period that the ship is moored, it will be in contact with fenders.

The experience of those responsible for mooring operation shows that there is a typical mooring configuration. And in this configuration, there are three different types of hawsers, separated by their functions and positions: the stern or head hawsers, the breast hawsers and the spring hawsers. Figure 1 and Table 1 illustrate these types of hawsers.

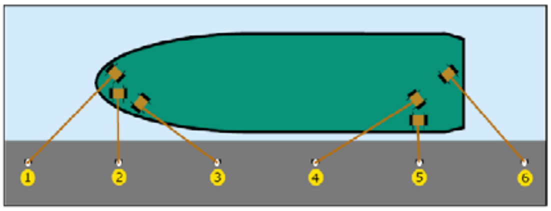

Figure 1 – Layout of the different types of hawsers

Table 1 – Definition of the types of hawsers corresponding to the figure 1

	Name	Function
1	Head	Prevents ship's moving backward
2	Breast	Prevents transversal movements
3	Spring	Prevents ship's moving forward
4	Spring	Prevents ship's moving backward
5	Breast	Prevents transversal movements
6	Stern	Prevents ship's moving forward

3 - The mechanical problem

3.1. Wind force

In the mooring operation, it is the external forces that cause the ship's movement and, consequently, it generates a reaction force in the hawsers and deform them. The main external force addressed in this paper is the force generated by the action of the wind. Especially if it is considered that the ship has a sail area of great importance.

Other important force for the moored ship are the current forces and the wave forces. Another force that has been subject in several papers is the force generated due to another ship passing nearby. Given the type of vessel that will be used as an example, a static model is proposed, and the wind will be the only external force.

Knowing that a moored ship is subjected to a wind and the wind speed is known and equal to V, it is possible to calculate the wind force on the ship. Equation 1 shows the relation between the resulting force and velocity oh the fluid.

$$F_D = \frac{1}{2} * \rho * V^2 * C_D * A \qquad (1)$$

In this equation, F_D is the drag force resulting from a flow of a fluid with density equal to ρ at a velocity V. As the fluid studied is air, the density used is equal to 1.223 kg/m^3. The variable named A is equal to the surface exposed to this flow. The last element is the drag coefficient C_D between the fluid and the surface studied. It depends on the shape of the surface and it is different in each ship.

There are several methods in order to assess C_D. It is the subject of many paper and studies, such as Ueno *et al*, Chen *et al* and Haddara *et al*. Among the various methods, some stand out because they are more precise than others.

Regardless of the method used to find the aerodynamical drag coefficients, a C_x, C_y and C_n (coefficient related to the moment) will be found to calculate the resulting forces in the main direction (X and Y) and to calculate a moment applied on the ship (moment around the Z axis). Equations 2, 3 and 4 demonstrate how it is possible to calculate these two forces and the moment from equation 1.

$$F_x = \frac{1}{2} * \rho * V^2 * C_x * S_{transv} \qquad (2)$$

$$F_y = \frac{1}{2} * \rho * V^2 * C_y * S_{longi} \qquad (3)$$

$$M_z = \frac{1}{2} * \rho * V^2 * C_n * S_{longi} * LOA \qquad (4)$$

S_{longi} e S_{trasnv} are the projections of the ship's surface in the longitudinal and transversal planes respectively. Figure 2 shows the orientation of the axes.

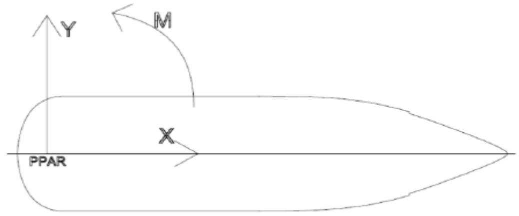

Figure 2 – Axis Convention. PPAR shows the aft perpendicular of the ship.

After being subject to the wind force, the vessel will react to seek an equilibrium position.

3.2. Ship reaction

Assuming the ship is a rigid body, it will not deform throughout the process. The only reaction it offers is its movement (which can be divided in the X and Y directions) and a rotation. The figure 3 shows the initial position of the vessel and the figure 4 shows the final position.

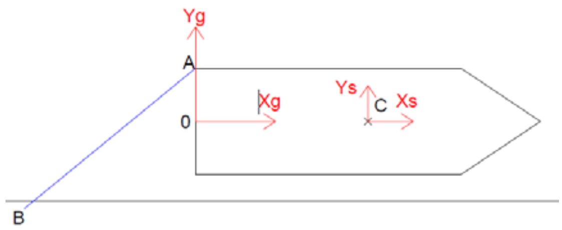

Figure 3 – Ship's initial position

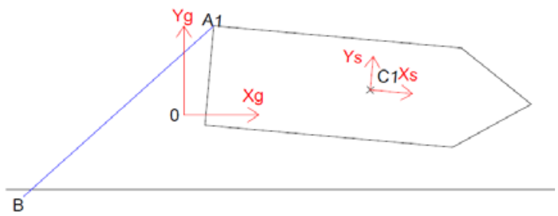

Figure 4 – Ship's final position

To perform the calculations, there are two reference axes. Point C shows the center of the ship's reference axis and point 0 shows the center of the global reference axis. Point B and A represent the trajectory of a hawser. Where point B would be a bollard and point A, a fairlead. The points A1 and C1 show the new position of point A and C after the ship movement.

The determination of the new point C1 and A1 is done through geometric calculations, assuming a known displacement (U_x and U_y) and a known rotation (θ). For this, the coordinate of each point is divided into the X and Y axes. Equations 5 and 6 show how find point C1 coordinates.

$$C_{1x} = C_x + U_x \quad (5)$$

$$C_{1y} = C_y + U_y \quad (6)$$

For the determination of point A1 coordinates, it is considered that it is equal to the coordinates of the vector $\overrightarrow{0A_1}$. In this way, it is possible to find these coordinates from equation 7.

$$\overrightarrow{0A_1} = \overrightarrow{0A} + \overrightarrow{AA_1} = \overrightarrow{0A} + \overrightarrow{AC} + \overrightarrow{CA_1} = \overrightarrow{0A} + \overrightarrow{AC} + \overrightarrow{CC_1} + \overrightarrow{C_1\,A_1} \quad (7)$$

The vector $\overrightarrow{CC_1}$ is equal to the displacement of the vessel, as shown in equation 8. The vectors $\overrightarrow{0A}$ and $\overrightarrow{AC}$ can also be described in the form of coordinates as shown in equations 9 and 10.

$$\overrightarrow{CC_1} = \overrightarrow{CC_1}x + \overrightarrow{CC_1}y = (U_x, U_y) \quad (8)$$

$$\overrightarrow{0A} = \overrightarrow{0A}x + \overrightarrow{0A}y = (A_x, A_y) \quad (9)$$

$$\overrightarrow{AC} = \overrightarrow{AC}x + \overrightarrow{AC}y = (A_x - C_X, A_y - C_y) \quad (10)$$

To determine the coordinates of point A1 it is also necessary to know the vector $\overrightarrow{C_1\,A_1}$. Therefore, the rotation of the ship is used as shown in equations 11, 12 and 13.

$$\overrightarrow{C_1\,A_1} = \overrightarrow{C_1\,A_1}x + \overrightarrow{C_1\,A_1}\,y \quad (11)$$

$$\overrightarrow{C_1\,A_1}x = (A_x - C_x) * cos\theta - (A_y - C_y) * sin\theta \quad (12)$$

$$\overrightarrow{C_1\,A_1}y = (A_x - C_x) * sin\theta + (A_y - C_y) * cos\theta \quad (13)$$

Finally, applying the results of the last three equations in equation 7, the coordinates of point A1 are found, as shown in equations 14, 15 and 16.

$$\overrightarrow{0A_1} = \overrightarrow{0A_1}x + \overrightarrow{0A_1}y \quad (14)$$

$$\overrightarrow{0A_1}x = 2A_x - C_x + U_x + (A_x - C_x) * cos\theta - (A_y - C_y) * sin\theta \quad (15)$$

$$\overrightarrow{0A_1}y = C_y + U_y + (A_x - C_x) * sin\theta + (A_y - C_y) * cos\theta \quad (16)$$

In the same way that the displacement of point A has been determined, it is possible to determine the displacement of all other mooring equipment present on the ship knowing only its initial position relative to the center of the ship.

3.3. Hawser reaction

With the external forces acting on the ship, it will move. With this movement, the winches, the double bollards, the rollers and the fairleads will also move along with the ship. In consideration of the calculation method used in this work, a hawser necessarily passes through a winch (or double bollard), a fairlead and ends in a bollard. The passage of a hawser thought a roller is optional. However, in the bellow explanation about the deformation of the hawser, it considers that the hawser also passes through a roller. With this, the more complex situation is addressed, which will also make understandable the resolution of when the hawser does not pass through the roller.

A hawser in the initial state will pass through a maximum of 4 points as shown in figure 5.

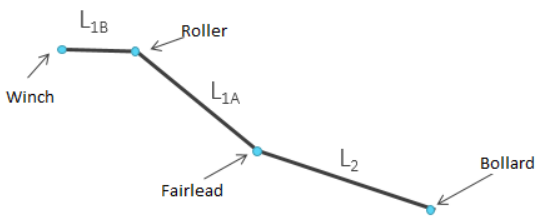

Figure 5 – Hawser in the initial position

From these three lengths, it is possible to calculate the total length of the hawser (L) which will be described as shown in equation 17.

$$L = L_{1B} + L_{1A} + L_2 \quad (17)$$

After the ship's movement, the lengths L_{1A} and L_{1B} remain the same, since the mooring equipment on board keep the same relative distance between them. On the other hand, the length between the fairlead and the bollard will change and the new length will be called L'_2. To better illustrate, the figure 6 shows the hawser after deformation.

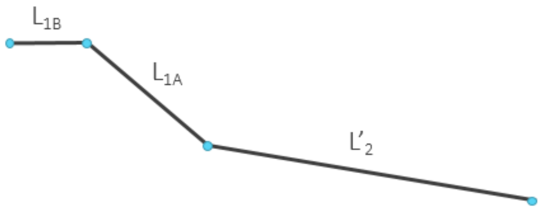

Figure 6 – Hawser after deformation

And then, the new total length of the hawser, called L', will be calculated as shown in equation 18.

$$L' = L_{1B} + L_{1A} + L'_2 \tag{18}$$

By analyzing the difference between the total lengths in the initial state and after the ship's displacement, it is possible to note that this difference only depends on the distance between the fairlead and the bollard in both situations. By calling this difference of ΔL, we observe the relation of equation 19.

$$\Delta L = L' - L = L'_2 - L_2 \tag{19}$$

This result will be used in equation 20, which shows how to calculate the final deformation of the hawser.

$$\varepsilon = \frac{\Delta L}{L} \tag{20}$$

With the deformation defined, its value is applied in the material curve that shows the relation between force and deformation. An example of this curve can be seen in the figure 7. This curve is obtained with the hawser suppliers and it is, in general, the result of traction tests.

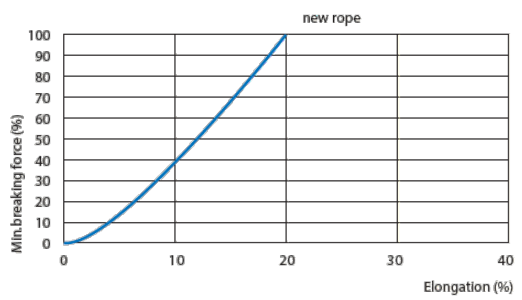

Figure 7 – Example of a curve of relation between force and deformation

Using this curve, it is found the value of the force applied to the hawser. The direction of the force is given by the direction of the hawser axis. This direction is found using geometric coordinates (on the X, Y and Z axis) of the fairlead and the bollard. Thus, the vector $\overrightarrow{Fa}$ is found and can be decomposed in three directions, as shown in equation 21.

$$\overrightarrow{Fa} = \overrightarrow{Fa_x} + \overrightarrow{Fa_y} + \overrightarrow{Fa_z} \tag{21}$$

The hawser force also generates a moment on the ship, around the Z axis. To find out the intensity of this moment, it is used the decomposed forces multiplied by the distance (also decomposed on the principal axes X and Y) in relation to a point (in general the ship's center, or any other arbitrary point). This moment is named Ma.

The force and moment found represent the value for only one hawser. Making the sum of all hawsers, it is found the force and moment that the hawsers are applying on the ship.

3.4. Forces balance

If the geometric data of the ship is given as input and the properties of the hawsers are known, the problem is simplified in only one relation between the external and hawsers forces and moments, defined in three equations. Then, by using Newton's law to guarantee the equilibrium of the ship after being subjected to the force of the wind, the equations 22, 24 and 25 are found.

$$\overrightarrow{Fw_x} + \sum_i \overrightarrow{Fa_{xi}} = 0 \tag{22}$$

$$\overrightarrow{Fw_y} + \sum_i \overrightarrow{Fa_{yi}} = 0 \tag{23}$$

$$\overrightarrow{Mw} + \sum_i \overrightarrow{Ma_i} = 0 \tag{24}$$

In those equations, $\overrightarrow{Fw_x}$, $\overrightarrow{Fw_y}$ and $\overrightarrow{Mw}$ are the wind forces and moment. And i represents each hawser.

Through the deductions made before, it is known that the hawser force and moment can be determined if the ship movement is known. Thus, a method to solve this problem is to assume displacements and rotations to find equilibrium positions.

Figure 8 presents a flowchart that represents how to find the external forces being applied on the ship from the assumption of a displacement and rotation.

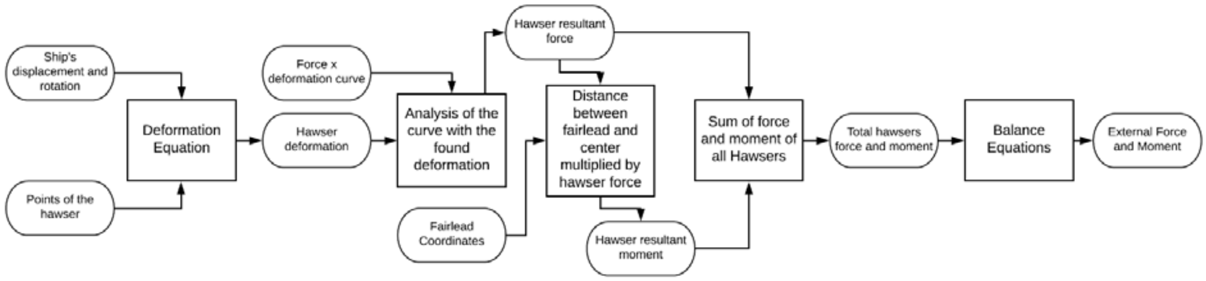

Figure 8 – Flowchart of the mechanical problem solution

Complementing this flowchart, figure 9 shows, through another flowchart, how to transform the force and moment found in a wind speed.

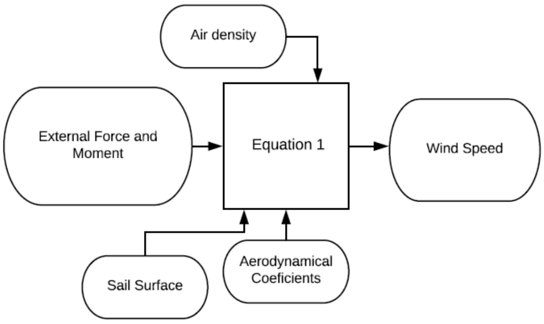

Figure 9 – Flowchart to find the wind speed

4 - Calculation method

To determine the highest wind, speed a vessel can support assuming a certain mooring configuration, a unique supposition of displacement and rotation is not enough. It is necessary to make several assumptions to find the one with a maximum wind speed and without a hawser breaking.

It is also necessary to find, besides the wind speed, the direction in which this wind will be acting on the ship surface. For each wind direction there are different aerodynamical coefficients, which implies a different wind resistance force each direction.

The method requires as input data the ship's main dimensions, the projected sail area in the longitudinal and traversal direction, the aerodynamical coefficients of the vessel, the position of all mooring equipment, the pier's main dimensions, the material of each hawser and its maximum tension.

Using all this information, the method outputs a report containing the maximum wind speed supported by the ship in 17 different directions. These directions vary 180°, between the bow wind to the stern wind, passing through the transversal wind that moves the ship away from the pier. The idea is to get several different directions, where none of them is a wind that pushes the ship against the pier. Others information are also present in the results, such as the force applied in each hawser for each of the 17 cases.

The flowchart shown in figure 10 shows how the method performs its iterations to obtain the results.

For each calculation case, the method performs around 10 thousand iterations before applying the stopping criterion. These iterations take about 1 minute to complete. After all the iteration have been performed, the stored results are displayed.

Figure 11 shows the results of an example using the method. The results are assembled in a radar chart for easy visualization.

It is important to emphasize that this method was done considering the recommendations of the "Mooring Equipment Guidelines – OCIMF" and the results were compared with the methodology proposed by the OCIMF.

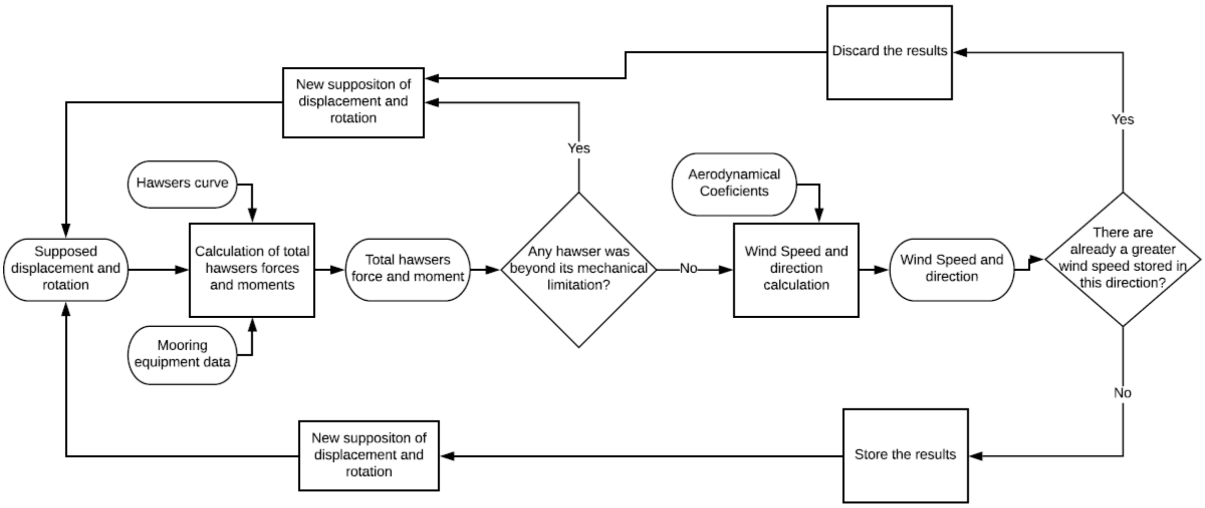

Figure 10 – Flowchart of the calculation method

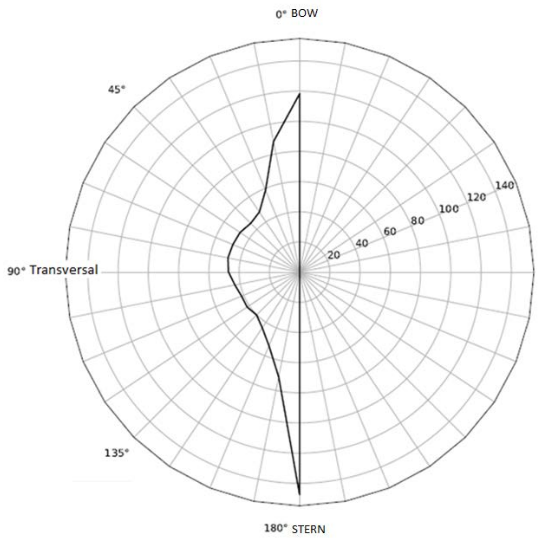

Figure 11 – Example of the method result in a radar chart

5 - Case study

5.1. Input data

For the analysis that will be described by this present paper, a ship and a pier, both theoretical, were chosen.

The vessel chosen was a Ferry which has the following characteristics:

- LPP = 170m
- LOA = 186m
- B = 27.3m
- T = 6.5m
- Displacement (Δ) = 19264t
- Longitudinal Sail Surface = 4263m^2
- Transversal Sail Surface = 1000m^2

Aerodynamical coefficients data used to perform calculations with this vessel were taken from the book “Manoueuvring Technical Manual”. This book has several aerodynamical profiles of vessels, where they are separated by type and length of vessel. Figure 12 shows the data that was used for the analysis.

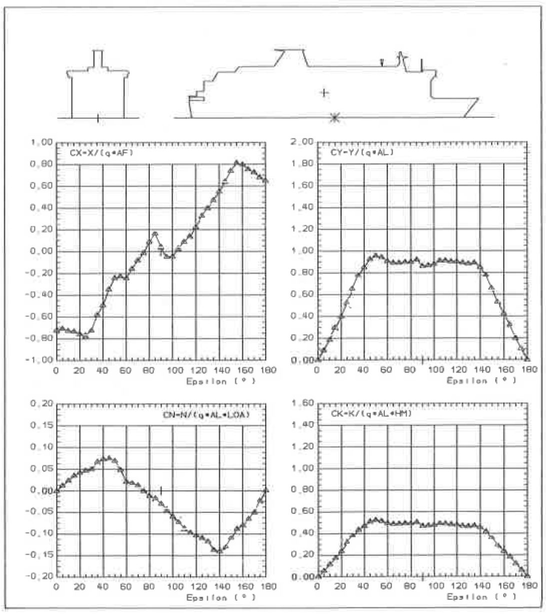

Fig. 1.15: Passenger/car ferry; L_{pp} = 144,00 m; L_{oa} = 161,00 m; B = 29,00 m; T = 6,05 m; AL = 4223,29 m²; AF = 898,21 m²; SL rel. to main section = −5,90 m; SH rel. to above water-line = 14,85 m; IfS

Figure 12 – Aerodynamical coefficients curve. Extracted from the book “Manoueuvring Technical Manual”

Figure 12 shows 4 tables, one for Cx, another for Cy, another for Cn and the last one for Ck. Only the first 3 are used in the present method.

5.2. Discussions

As shown in figure Figure 1, a hawser can exert some different functions. The purpose of this analysis is to determine whether there is an interest in using more breast hawsers than the other types of hawser.

Professionals who perform the mooring operation, have the habit of use the same number of hawsers for each type. The typical configuration for the vessel of the present analysis would be to use two head hawsers, two stern hawsers, two forward breast hawsers, two aft breast hawsers, two forward spring hawsers and two aft spring hawsers.

This analysis will have 4 different scenarios to verify the wind resistance with different mooring configurations, but with the same number of hawsers, that is 12 hawsers. The first scenario, called Sn1, will be the typical configuration described in the previous paragraph.

The second scenario, called Sn2, will change the trajectory of two hawsers in relation to the first scenario, making them act as breast hawsers instead of head or stern hawsers.

The third scenario, called Sn3, will change the trajectory of four hawsers in relation to the first scenario, making them act as breast hawsers instead of head or stern hawsers.

The fourth scenario, called Sn4, will change the trajectory of four hawsers, making them act as breast hawsers instead of head or stern hawsers and four other hawsers making them act as breast hawsers instead of spring hawsers. It means that all hawsers will be acting as breast hawsers in this scenario.

For a better visualization of the changes made between scenarios, figures 13, 14, 15 and 16 represent the initial position of the ship in each scenario.

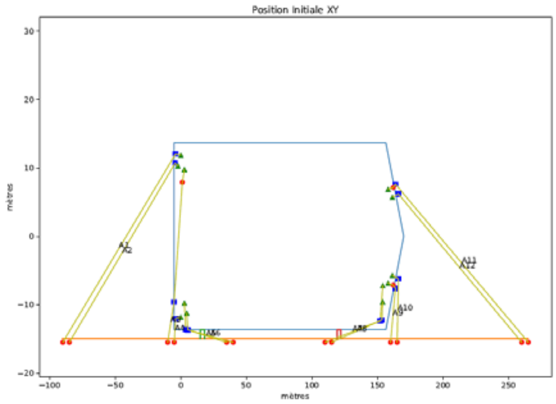

Figure 13 – Ship's initial position for the Sn1

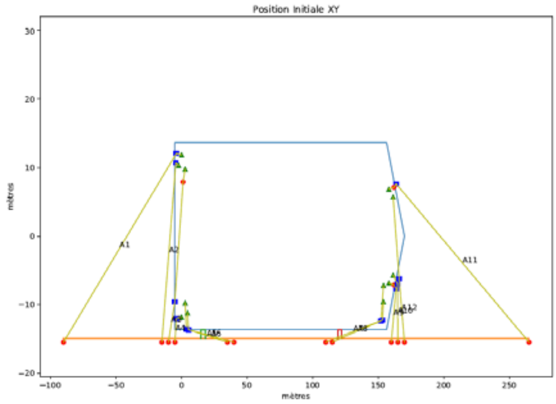

Figure 14 – Ship's initial position for the Sn2

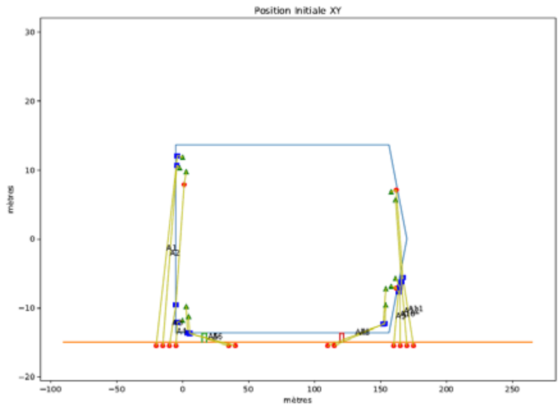

Figure 15 – Ship's initial position for the Sn3

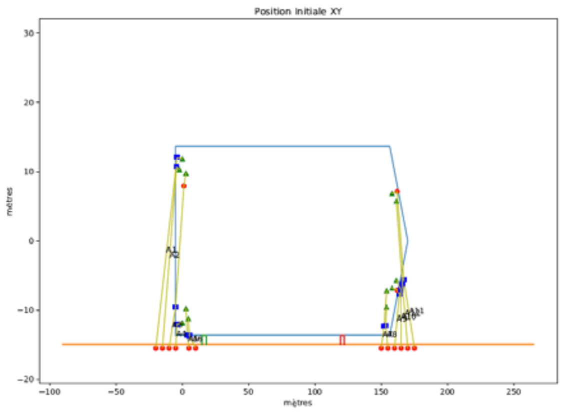

Figure 16 – Ship's initial position for the Sn4

5.3. Results

After performing the calculations for each scenario, the maximum wind speed is taken from the results report. Table 2 present the wind speed results for each scenario and wind direction. The highlighted cells are the results that present lower speed in each case. This means that the ship resists at least to that wind speed in any direction.

Table 2 – Results of the wind speed

	Sn1	Sn2	Sn3	Sn4
Wind Dir. (°)	Wind Speed (knots)			
0 (Bow)	111.8	143.26	143.16	93.78
11.25	82.69	92.5	104.16	112.17
22.5	55.41	68.02	73.82	83.05
33.75	44.86	53.25	58.08	65.35
45	42.87	47.06	50.81	55.9
56.25	42.7	49.85	52.88	59.4
67.5	43.08	51.81	57.21	62.96
78.75	42.18	53.28	57.52	64.75
90 (Transv)	40.6	52.82	57.93	59.81
101.25	38.33	54.29	60.45	57.84
112.5	36.96	52.71	60.16	55.89
123.75	37.11	48.62	56.22	51.64
135	35.17	46.5	52.71	49.23
146.25	38.89	51.46	59.46	65.77
157.5	46.31	70.39	80.67	84.88
168.75	65	108.22	132.04	116.03
180 (Stern)	133.94	155.19	150.88	113.74

The results might also be organized in a single radar chart, where the curves show the maximum wind speed in knots, as shown in figure 17.

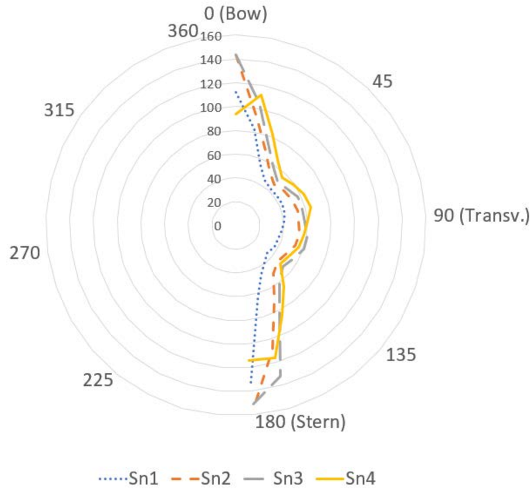

Figure 17 – Radar Chart with the analysis results

The results show that there is a strong relation between the choice of type for each hawser on the mooring configuration and the wind resistance. After the increase of the breast hawsers number, replacing the others hawser type, there was an improvement in the wind resistance.

The numbers show that changing the typical mooring configuration (Sn1) by the configuration of Sn2, there is a 32% increase in wind resistance in the direction of 135°, which is the limiting direction in this case. When the Sn3 is applied, the value increases by 9% comparing to the Sn2, but the limiting direction becomes 45°. And when all hawsers are breast type (Sn4), there is a decrease in wind resistance of 3% compared to the Sn3, returning to the limiting direction of 135°.

Considering the difference between the results of the Sn1 and the Sn3, which are the lowest and the highest value in the analysis, there is a 44% wind resistance variation.

It is possible to conclude that increasing the breast hawsers number is rather something to be done to improve the mooring configuration. But there is a limit and using all hawsers as breast type would not give the best results. There exists, between these two scenarios (Sn1 and Sn4), a scenario that gives the optimal mooring configuration that the ship can use.

This conclusion is explained by the fact that the most limitans wind directions are those close to the transversal direction (90°). In those cases, the wind acts in a larger sail surface when compared to the extremities winds (0° and 180°). Knowing that the breast hawsers are the ones that mainly resist this direction of wind, while the other types of hawsers tend to resist to the extremities wind, it is understandable that when the mooring configuration has more breast hawsers, the wind resistance is greater.

It is possible to observe that in Sn3 there is a variation of the limiting wind direction. However, in this scenario, the wind speed for 135° direction was equal to 52.71 knots, very close to the limiting value, which would also validate the conclusion. In addition, the 45° direction is the symmetrical direction of 135°, if 90° is considered the center. This means that those two directions will have close results if the mooring configuration tends to be symmetrical between stern and bow, as is the case with this analysis.

6 - Conclusion

This paper first shows the importance of the study of mooring for a ship. This operation requires resources (time and mooring equipment's) and it is carried out regularly so that it can be a source of CAPEX and OPEX reduction. Given the history of this activity, several practices and recommendations are known to those professionals responsible for the operation. However, a theoretical study is also necessary to improve existing techniques.

Several approaches are possible to solve the mechanical problem. Studies can use all external forces together or focus on one external force so that only the most influential force will be studied. It is necessary to know the objectives of the study to choose the best approach.

Once the resolution method is chosen, there are still a considerable number of variables to determine. The choice of these variable directly influences the outcome and cost of the ship's operation and construction. Analyzing the variables separately is a good way to better understand the sensitivity of the problem and to understand where an optimization would work better.

The present paper analyzed the influence of the number increase of the breast hawsers for the wind resistance of the ship. The result shows that there is a possibility of increasing wind resistance by up to 44%. A relatively high resistance that can be obtained only by changing the mooring configuration. This analysis shows that is possible to change the mooring configuration of a ship to increase wind resistance without making big changes and without adding extra hawsers.

With the result obtained in this paper, other opportunities can be seen in the analysis of the calculation of the mooring of ships. Continuing the analysis, conducting a larger number of calculations or modifying the analysis approach is important to perpetuate the conclusion of the results.

Moreover, since the analysis was performed using a specific resolution method, it is interesting to compare those results with the results obtained by performing the same calculations in other methods and in other software. Or even perform experiments that can measure these values in a real mooring to test the effectiveness of these data with reality.

The analysis shows that there is a way to improve the mooring configuration for better wind resistance. However, it would be interesting to analyze the financial effect of these changes. It could avoid some extra hawsers and thus save costs.

It is also worth mentioning the idea of optimization of variables. As seen for the number of breast hawsers, there is an optimal number of hawsers that guarantee a maximization of wind resistance. This is undoubtedly an area to be explored.

7 - Bibliography

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