Construction of a Small-Scale Tugboat

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Abstract

Support vessels for other ships emerged to provide specialized assistance in port logistics. Among these support vessels are tugboats. In this logistics, a tugboat that has an ineffective propulsive system will cause poor support, bringing losses to the sector's production chain. The problem addressed in the work aims precisely to present the construction process of tugboats as complex and dynamic, but at the same time allows to achieve very favorable results in terms of teamwork and the use of computer simulation in the process of projecting parts and components. This work presents the process of building a tugboat on a reduced scale, the elements mentioned here are valid for the construction of tugboats at any scale, which reaffirms the importance and topicality of the theme addressed. The procedures for the construction of the 2017 naumodel were described. Hull designed in DELFTship. The construction of the tug was made by cuts in welded 3mm aluminum sheets. The propellers designed using 3 software: NavCad, PropCad and SOLIDWORKS, cast through 3D molds printed on ABS molds. Magnification box designed, using parameters from NavCad results, in Autodesk Inventor, model 1:1.2. Axis and alignment of the motors carried out in order to reduce the maximum losses.Palavras chaves: rebocador, projeto mecânico.

Introduction

Brazil has an interesting naval history. This narrative goes from the private initiative of Visconde de Mauá, in the naval enterprises until the peak of this industry in 1970, in its decadence during the periods of the 1980s and 1990s, until its strengthening near the 2000s. During its strengthening at the end of the 1990s, the naval industry developed due to offshore oil exploration. The Petroleum Law and the Navega Brasil Program were created precisely as a stimulus to the Brazilian naval industry during this time. These two stimuli created the conditions for Petrobras to increase its demand for offshore support vessels [7].

The demand for offshore support vessels tends to increase until 2020 [3]. This includes PSV-type vessels, which were significantly manufactured in Brazil in 2014 [1]. This vessel operates in diverse situations and its propulsion system must be prepared to operate according to the variations imposed on the propulsion installation.

The propulsion installation can be classified, metaphorically, as the "heart" of a ship. Choosing the proper propulsion arrangement and sizing its components is of paramount importance for the operation of the vessel. Maximizing efficiency provides cost savings related to materials, and the choice of functional elements and appropriate machinery. Small variations in efficiency increase may seem negligible, however, due to the high-power consumption of marine engines, this efficiency increment represents a large share of economy in operational terms [15].

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The problem posed to the work team was to design a small-scale towing boat that would be powerful and at the same time fast enough to participate in a university competition for this type of boat.

The aim was to design a powerful and fast tugboat. These vessels are of great robustness, high machine power and good mobility, intended mainly for towing, being able in some cases to provide other assistance, such as firefighting and sewage services [6].

In possession of the previous need it is proposed as an objective to develop a tugboat project according to the conditions established for this event: power and speed according to the normal practice of developing projects of this type.

Development

Bollard Pull can be translated as static pull and represents the static towing capacity of a vessel. The test is done using a cable tied to the boat and to a fixed point, usually a bollard, and a load cell is used for measurement. Bollard Pull is an "abstract" state that cannot be achieved in real operation due to two factors: the first is that propellers change water speed as they rotate, so they never "see" the water at zero speed, and the second is that engines cannot achieve maximum RPM at towing speeds due to a decreasing RPM versus torque ratio. [12].

The mooring stake condition, however, is generally used as a "merit criterion" for towing applications, where, in other words, even if it is never achieved, propulsion in the tug condition provides a simple means of comparing one propeller to the other in a towing scenario.[13]

During testing, one should make sure about the safety of the chosen location, the tensile strength of the cable, the weather conditions, where these are standardized by the classifiers, as it can directly affect the result. As a reference for some test requirements for Bollard Pull, is given below technical information from Naval Sul Ltda [11].

The most common types of tugs used in the market are given below: Azimuth Stern Drive (ASD) (Zpeller): is a tug with conventional propellers, and shaft lines that can be replaced by azimuthal propulsion units, which has a turning power of 360 degrees around the vessel's axis.[2]

Tractor tugs: the term "tractor" is used for those vessels where the propulsion unit is located one -third of the way forward, and is the main difference to ASD type tugs.

Tractor tugs can be of the Voith Schneider type (VS) or with azimuthal propulsion unit (TAT).

Voith Schneider Propeller (VSP): with cycloidal propellers that rotate around a vertical axis, being similar to the rotors of a helicopter, which brings great maneuvering power to the operators.

Tractor Azimuthing Tugs (TAT): emerged in the 1970s as an alternative to replace the Voith Schneider system, being propelled by non-cycloidal rotating propellers.O Sistema de hélices convencionais e muito usado em Embarcações convencionais com um ou dois eixos hélices, porém tem manobrabilidade limitada por isso este tipo de propulsão utilizada somente para vante, não permitindo alterações de rumo.[8]

The tubular type system allows for an increase in the Bollard Pull condition, being provided with a tubular protection around the propeller, which can be fixed or mobile, used in conventional tugs, tractor units, and reverse propulsion. It is not used on Voith Schneider system vessels.

The controllable-pitch propeller type system has the advantage that it can be adjusted, increasing the desired thrust. Used on ocean-going, conventional, tractor and aft-propulsion vessels. [5]

The Azimuthal Propulsion system possession rotate at 3600; used in tractors, Harbour and Port Support, has excellent maneuverability mainly for mooring operations. [5]

Thrusters, in this type the propulsive system rotates around a vertical axis. There is a change in the angulation of the blades, changing the pitch; used in Tractors, its maneuverability is very good because the control of the operation is superior to other types of systems, but the Bollard Pull xBHP ratio is low. [9].

The Bow Thruster system is installed ahead of the vessel, provides lateral movements, increasing maneuverability, improving the functionality of tugs; it is used in all types of vessels, except for tractors. It is not usually used, being supplied in the projects by azimuthal propulsion. Widely used in terminals with large movement due to the increase in maneuverability. In Brazil there are no tugboats with this type, but it is widely used in offshore support vessels and has excellent maneuverability, especially if used with azimuthal propulsion. [14]

Methodology

The work was developed according to the following methodological sequence:

- Determination of the problem based on the problematic planteada and establishment of the objective of the same.
- Bibliographic review aiming to adopt the conceptual elements that provided an answer to the problem posed.
- Elaboration of the project's methodological sequence.
- Construction of the tugboat according to the project developed.
- Elaboration of conclusions.Resultados e analise.

The Work Team used DELFTship software to design the hull of the 2017 nautimodel. As defined by the team's criteria, after research, the hull was designed to have a tapered bow, as it would decrease forward resistance, and a wide/quinished parallel body, increasing its carrying capacity and keeping it stable.

Construction of the tugboat in reduced scale

- **Line plan**

For construction, the line plan was printed in full scale. The cuts were made in 3mm aluminum plates and joined by welding, thus giving the final shape of the hull.

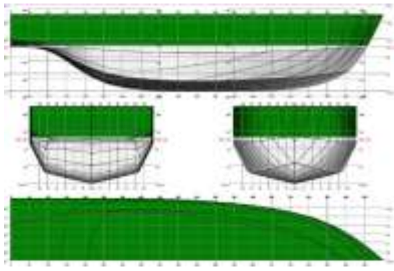
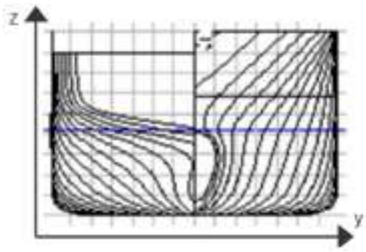


Figure 1: Line plan of the ship.Source: Authors, 20221

In a nutshell, the line plan is a series of curves that represent "cuts" of sections of a ship in the three orthographic views - front, top and side - with the peculiarity of containing, in each view, lines that show the positioning of the cut planes of the other two views.

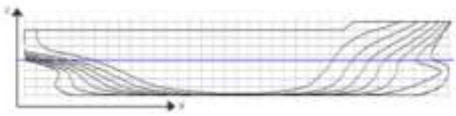
The line plan, the initial step of the work, is a projection system in orthogonal views that aims to represent the main features of the hull shape, so that all its geometry can be represented in three planes: beacon planes, top line planes and waterline planes. These show the intersections respectively with the transverse vertical plane, the longitudinal vertical plane, and the longitudinal transverse plane.[10]

The Beacon Plane exposes the front view of the hull. That is, it is defined by the YZ plane and represents the cross sections of the ship. Its contour is determined by the maximum horizontal and vertical measurements, which will be, respectively, the mouth (B) and the maximum deck height (including false edges), which we will call H (H x B). The beacons from the main section to the bow are represented on the right side, while those from the main section to the stern are represented on the left side. This can be donebecause of the symmetry found in ships.



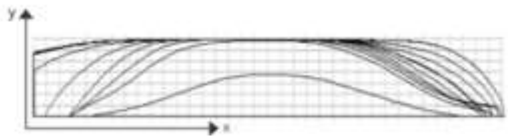
Beacon plan. Source: Authors, 2021.

The Top Line Plane shows the side view of the ship. That is, it is defined by the XZ plane and represents the intersections of the hull with the longitudinal vertical plane. By convention. The ship is drawn with the stern on the left side of the sheet. The outline will be defined by the total length (Loa), horizontally, and the maximum height H, vertically, (Loa x H).

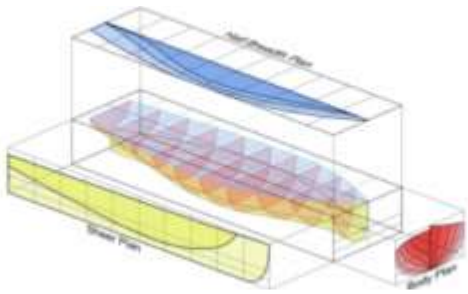


Line plan from above. Source: Authors, 2021.

The Waterline Plane shows the top view of the ship. That is, it is defined by the XY plane and represents the intersections of the hull with the longitudinal transverse plane. Despite the ship's transverse symmetry, a rectangle with horizontal and longitudinal dimensions (Loa x B) will be drawn. One edge will illustrate the waterlines, plus the outermost outline of the hull (usually the deck), while the other will contain the bulge diagonal.



Water Line Plan o. Source: Authors, 2021



The three planes in isometric perspective. Source: Authors, 2021.

Next, the water line plan must be drawn, starting with the corners. To draw a corner, based on the tracing of the beacons in the goal plane, take the horizontal distance at which each beacon intersects the corner, and mark this distance on the vertical of the respective beacon in the waterline plane, and finally join the points as smoothly as possible. The procedure for drawing the T/4, T/2, etc. waterlines is analogous, i.e., the horizontal distance at which each waterline intersects a mark (or a corner) is transferred to the respective mark (or corner) on the waterline plane, and then the points are joined. At this point it is important to pay attention to the starching, because the points where the waterlines intersect the corners and the hull edge must coincide in all 3 planes.

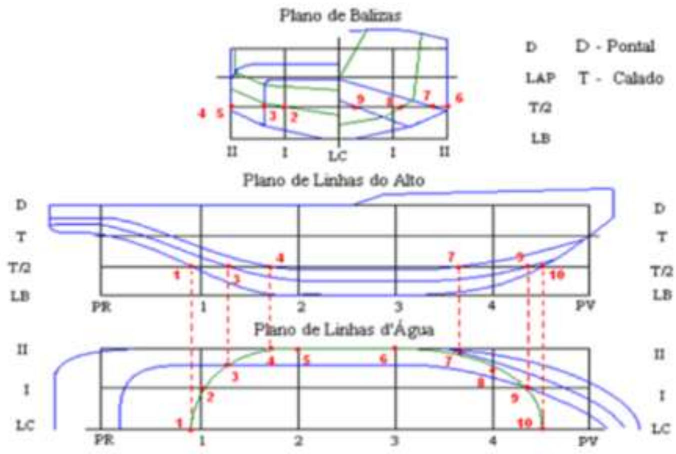


Figure. Water lines. Source: Authors,2021

Propulsion

Among the main parts of a ship is the propulsion system. With a well-functioning propulsion system one obtains huge gains in several aspects such as reduction of fuel consumption, speed, bollard pull among others[16].

For this model, as it belongs to the tug class, the focus was to design a propeller that would result in the highest possible thrust.

- **Propeller selection process**

- The Kaplan series was chosen due to its requirements that, combined with the use of the Kort Tube, increase thrust and favor vessels that require high bollard pull.

The process for defining the model to be used was in 3 parts:

1. Analysis in HydroComp NavCad software;
2. Modeling in the HydroComp PropCad software;
3. Simulations in SOLIDWORKS software;

- **Modelagem e simulação computacional do rebocador**

Analysis in HydroComp NavCad software

In this phase the hull information (obtained from the DELFTship program) and the engine information available in the competition notice were used to verify which models in the image below would obtain the best results. Several 3.65 and 4.7 models with variations in pitch, diameter and area were used. After comparisons, the models were selected to be modeled and then simulated.

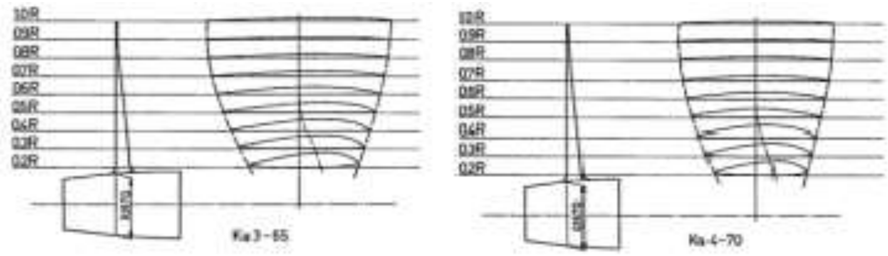


Figura 3: Design de Pás da Série Kaplan.

Modeling in HydroComp PropCad software

With the models selected and all their specifications, the next step was modeling. For this, the PropCad program was used. Through it, the selected propellers took shape. The premise of the program is simple, the user enters a series of values and the software executes the desired propeller.

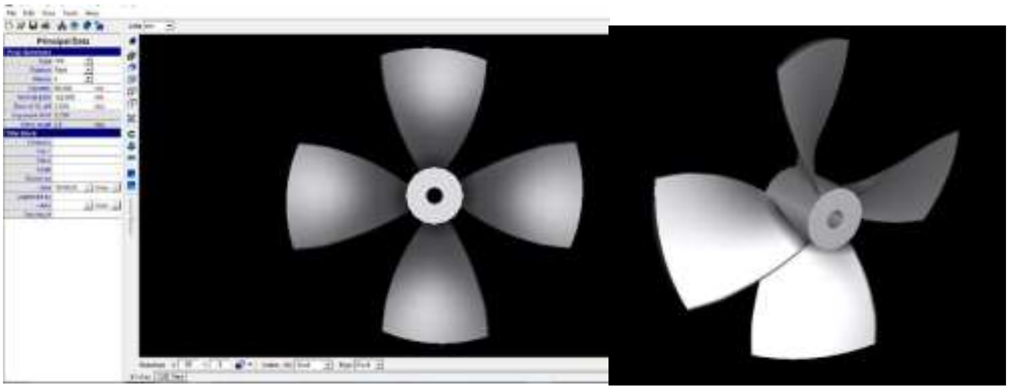


Figure 4: Model Produced in PropCad Software

Simulações no software *SOLIDWORKS*

Os modelos projetados no *PropCad* forsão mostrados a continuação foram exportados para o *SOLIDWORKS* e em seguida montados usando as ferramentas de costura d

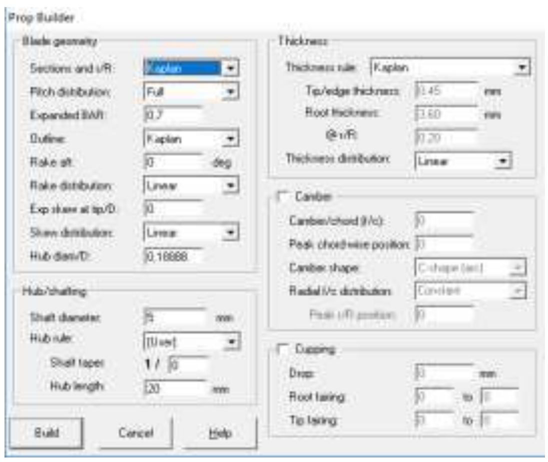


Figure 5: Data from 1 Model Used in the Program. Source: Authors, 2021

The software. After this process the FlowSimulation tool was used to verify the results of the flow, thrust, and pressure models.

Parâmetro	Mínimo	Máximo	Média	Área da Superfície [m²]
Pressão [Pa]	29563,11156	121285,7357	93782,38557	0,004368499
Velocidade [m/s]	2,558113922	13,30495323	8,325112085	0,004368499

Table 1: Results Obtained in Simulation of 1 Model. Source: Authors, 2022.

The simulation results are shown in figure 6.

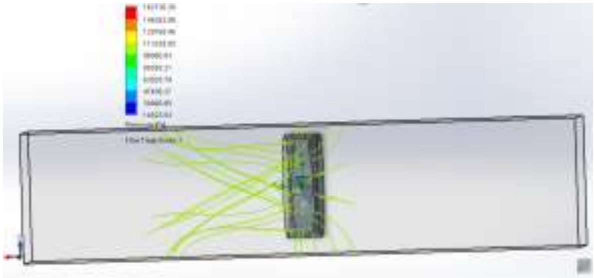


Figura 6: Resultado da Simulação de Escoamento de 1 Modelo. Fonte: Autores, 2022.

After the comparisons, the propellers with the best performances were selected for fabrication (casting) and then practical tests to define which would result in the best results, thus being the best model.

Model	Number Page	Diameter [mm]	Pitch [mm]	Ae/ Ao
Model 1	4	90	120	0.7
Model 2	4	85	108	0.7
Model 3	3	90	108	0.7

Table 2: Data from the Models Used in the Tests. Source: Authors,2022

- **Kort Pipe**

Like most real tugboat class vessels, the propulsion of the nautimodel uses the Kort Pipe to improve its efficiency. This tube is a cylinder that surrounds the propeller so that its cross-sectional area decreases from the inlet to the outlet, increasing the pressure and speed of the outflow. Other advantages of using the tube are improved maneuverability, increased thrust, reduced vibration, and propeller protection.

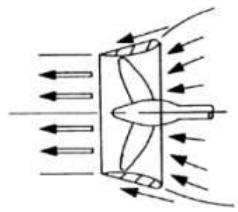


Figure 7: Flow Lines Through the Kort Tube. Source: Authors,2022.

The model used in the nautimodel was the Kort 37 Tube because it has the highest efficiency both forward and aft.

Figure 8: Project of the Kort Tube and its execution. Source: Authors,2022

- **Propeller selection process**

The sand casting process was chosen for the execution of the models. For this, it was necessary to first make a 3D printing of the model, so as to have a mold for the casting process.

The printing was done with the material: Acrylonitrile Butadiene Styrene - ABS, (commonly used in this process). Aluminum was used in the casting. The final piece also went through a finishing process to obtain the best possible result.

Figure 9: 3D Printed Model and After Casting. Source: Authors,2022**Testes**

To prove the efficiency of the propellers, a series of tests were conducted. Speed, strength, and maneuverability were the main factors taken into account in the tests (simulations of the competition races).

It was defined that Model 2 would be used in the competition because it obtained the best results with the kort tube.

MECHANICAL DESIGN OF THE PROPULSION

To find out which type of housing would be ideal for the project, a propulsion study had to be done in the HydroComp NavCad software. In this way it was possible to forecast the propulsion of the boat with the best performing propeller and, thus, determine the reduction or enlargement that would fit the conformities of the project.

Reduction/Enlargement Box

The reduction gearboxes are arrangements made by gears that have the function of decreasing the angular velocity, i.e., decreasing the number of revolutions that are transmitted in order to increase the torque. This system works with a larger gear coupled to the shaft that comes from the motor and a smaller gear that will be coupled to the shaft that transmits the rotation to the propeller. With this type of arrangement it is possible to obtain the necessary torque for which the project aims. This craft works with a gearbox that has basically the same purpose, but with the values reversed. The torque is reduced and the angular velocity is increased, in the same proportion.

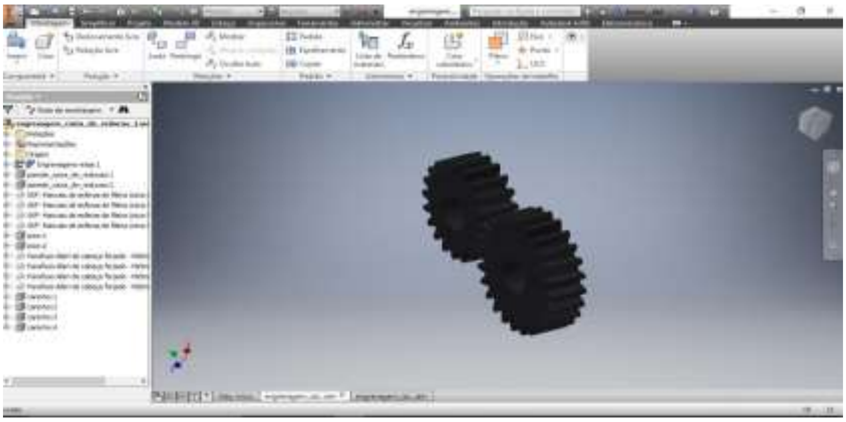
Construction

Knowing well the system's operation and knowing the values to be modified in the transmission to obtain the best possible performance, another software was used to design the parts of the enlargement box that the project wanted. In Autodesk Inventor each part of this system was assembled individually. The gear pair, the shafts that would execute this transmission change, the bearings to be used, the screws, the holes in the plates, and the finishing details, and after everything was ready, the system was assembled.

Figura 10: Projeto da Caixa de Ampliação. Fonte: Autores,2022

With the propulsion study, it was found that the ideal would be an enlargement of 1:1.2, i.e. to increase the engine speed by 20%, so that the engine that was running at 2900 rpm, after the enlargement the speed would be increased to approximately 3480 rpm. This change has a direct effect on the torque of the motor, which before the expansion had a torque of 0.8 N*m, now has a torque of approx. 0.64 N*m, running perfectly with a power of 0.243 kW in the largest gear and 0.238 kW in the smallest gear.

The gears designed with a module of 1.25 are of the cylindrical and spur type, one with 24 teeth and one with 20 teeth. This results in a pitch diameter of 30mm on the larger and 25mm on the smaller. They are made of polyacetal, a polymer that has good mechanical strength, resistance to stress, and a low cost, so these characteristics were essential for the choice of this material.Figura 11: Par de Engrenagens.



Source: Authors, 2021

The shaft used was a 5mm, silver steel shaft. With it, it was possible to align the motors in the most efficient way in order to reduce the losses in the electromechanical design.

- **Maneuverability**

1. Rudder Sizing

For the rudder sizing of the two-propeller boat, the criteria and formulations of the paper "A Practical Approach to Rudder Design" by B. J. Lamb and S. B. Cook from Shipbuilding and Shipping magazine were used. Based on the table, a factor of 2.5~4.0 was used.

With the data of cross-sectional area, waterline length and draught, and taking into account the presence of tubular and 85mm diameter propellers, the rudder area can be found by the following variation and formula:

p1x(LwlxT) < A < p2x(LwlxT)

[(T×Lpp)/100]×[1+25×(B/Lpp)^2]

The aspect ratio relates the rudder height and the middle chord and, for this type of ship, this ratio (AR) should vary between 1,3 and 2,5, to verify that the calculated dimensions are acceptable. Therefore, together with area, the following table can be assembled:

3,9	% L x T
L x T [m²]	0,11472
% L x T [m²]	0,00447
H máx. [m]	0,14167
H [m]	0,1

CM [m]	0,04474
AR	2,2351

Table 3: Maneuverability Tables. Source: Authors, 2021

The compensation must be between 26% and 30% of the average rudder chord, and be appropriate to the units:

26% [m]	0,011633	
30% [m]	0,013422	
Compensaçtion [m]	0,012527	
Percentage	28%	Valid

Table 4: Maneuverability Table. Source: Authors, 2021

1. Rudder Force

To calculate the normal force forward and aft, the equation proposed in the article under study [9] was used**.**

Normal force	$Q=N\times A\times v^2\times\theta$
N	0,035

Table 5: Table of normal force. Source: Authors, 2021

2. Torque

To calculate the torque, it is necessary to initially obtain the center of pressure, located at 35 degrees of the middle chord, then one obtains the torque arm or lever fore and aft, which when multiplied by the force will result in the torque:

T	0	ft.lbf	(a vante)	0,00318	N.m
	0	ft.lbf	(a ré)	0,00566	N.m

Tabela 6: Table of torque. Source: Authors, 2021

3. Rudder Shaft Diameter

For the rudder shaft sizing, the already calculated torque and the admissible stress of steel

1040 (rudder material) (220 MPa or 22 kgf/mm^2) were used, thus:

T = 0;

D	0,00063	ou	0,06287
	m		cm

Tabela 7: Sigma values. Source: Authors, 2021

4. Construction

A 0.6mm aluminum plate was used for the cuts and manufacturing of the rudders. For the shaft a 3/16 inch diameter shaft was used.

Figure 12: Rudders of the Nautimodelo. Source: Authors, 2021

Stability Calculations

Boat Name	Jaraqui II
Total length	1000 mm
Molded Mouth	330 mm
Molded Height	170 mm

Table 8: Hull Data. Source: Authors,2021

Vessel Components	Weight [g]	LCG [mm]	M*LCG [g.mm]	KG	M*KG [g.mm]
Light weight	8379	491	4114089		
Motor	2000	445	890000	53,63	107260
Battery	379	757,3	287016,7	21,63	8197,77
Servo Motor	69	105	7245	139,9	9653,1
ESC	39	594,5	23185,5	17,63	687,57

Amplification Box	200	335	67000	42,84	8568
Sum	13266		6345536,2		250194,44
Ballast	4734	LCG [mm]	478,3307855	KG	18,85982512

Table 9: Stability Data. Source: Authors, 2021

After the stability studies, we arrived at the best way to manage the ballast and reach the minimum draft required by the competition notice (12cm with 18kg of displaced volume) from the places that needed to be ballasted.

Since the boat is a two-propeller model, with two engines and two magnifying boxes, equally separated from the keel, it was not necessary to use a lot of ballast for the stern compared to the need for the bow.

- **General Arrangement**

The General Arrangement was developed using AutoCAD software. This way it was possible to previously visualize how all the necessary components would be fixed or allocated on the hull. Besides collaborating to inform the places that would possibly need ballast.

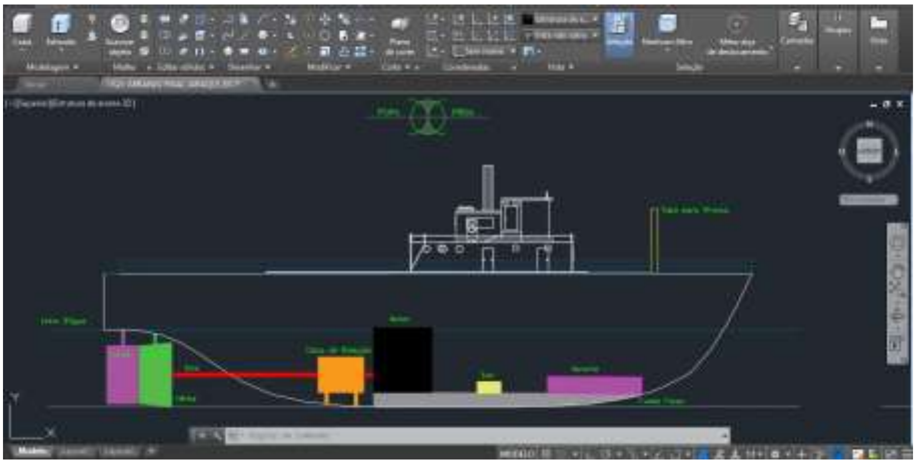


Figure 13: General Vessel Arrangement. Source: AUTORS,2021.

- **False bottom**

The false bottom was elaborated using a wooden plate. The solution adopted was to weld small hinge-shaped pieces of plate along the bow of the hull and screw the plate to them, thus making it possible to remove it for the addition or removal of ballast when necessary.

- **Ballast**

Ballast is a material used to increase weight and/or balance an object. In most boats fluids are used as ballast, due to the ease of removal and addition, according to the needs of each boat. If it came to our ship, the most feasible was the use of lead tape and ½ inch steel blocks.[8]

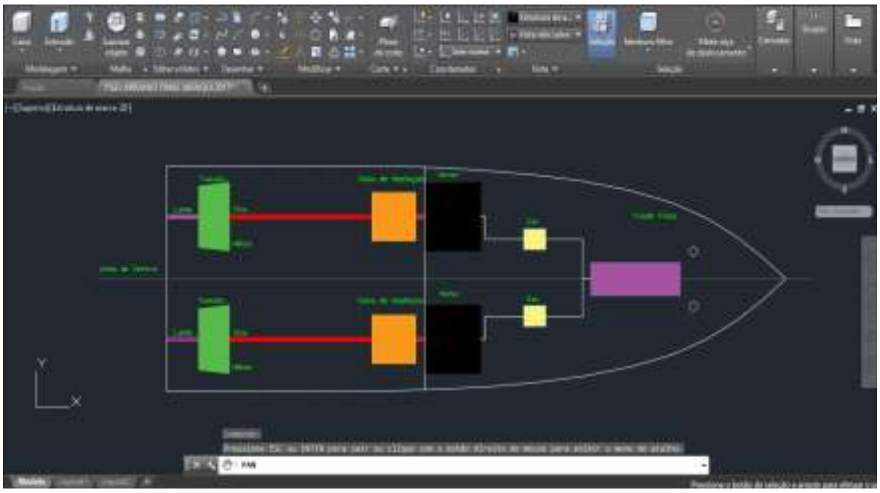


Figure 13: Super view of General Vessel Arrangement. Source: AUTORS,2021

The lead tape, because it is more compact and can be placed under the false bottom, located in the bow of the boat. For the blocks, we used leftover flanges cut with a blowtorch. Holes were drilled in the center, which fit in some places of the boat that have a small thread bar, welded to the hull, and consequently secured by a drill. And according to the needs of each race of the competition, changes will be made in the places predetermined by the stability team.

After the project was finalized in the software, it was continued to the manufacturing of the hull. Through the life-size prints of the isometric views, the Molongó fiber was cut. Finally, the project execution process involved painting and fixing the fiber.

The final result can be seen in the images below. A superstructure made with regional fiber that provided an ideal weight so as not to interfere with the stability of the boat during the trials.

Figure 24: Finished Superstructure. Source: Autorers,2021

CONCLUSIONS

The fulfillment of the project made it possible to develop a project capable of reaching the proposed objectives and, in turn, served to train the students of the team to act in their future professional areas, besides contributing to the growth of the university as a whole.

The rudder sizing was done and the steering system used a rod to connect to the servo motor. For the superstructure a regional material was used, the Molongó fiber, being very light and with a great resistance in general.

The project was completed after several turns in the project spiral, trying to reach the established goals, arriving then to the result presented in the competition.

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