THRUST ALLOCATION ALGORITHM FOR DP SYSTEMS CONSIDERING THE INTERFERENCE BETWEEN THRUSTERS ANS THRUST-HULL

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***Abstract**. The present work presents a thrust allocation algorithm for Dynamic Positioning (DP) systems that considers the interference between thrusters and thrust-hull. Therefore the thrust allocation tasks becomes more reliable, also the Dynamic Posiotining System, which guarantees stability and capability of floating platforms during offshore operations. To approach the problem of interference and implement it in the algorithm ,empirical methods avaliable in the bibliography were used. Also, to include this data in the algorithm a new model of the thrust allocation problem was developed in polar coordinates. Using polar coordinates method we were able to measure the efficiency of the thrusters in different angles, so we could allocate the thrusters to minimize power, evaluate the interference according to its cause (thrust-hull or thruster-thruster interference) and compare with the information avalable in the bibliography. The algorithm was tested numerically to evaluate the station keeping performance of DP vessels with this new thruster allocation method. The numerical analysis allowed us to create a computational program that can infer the capability plot for a vessel. This study brought the opportunity to know whether the use of the forbidden zone (where one thruster water jet hits another) can minimize the power of the ship when it is operating offshore. It also allowed us to represent the forbidden zone numerically, which made possible to compare with the thrust-hull interference and optimize the thrust allocation. This paper also presents solutions and analysis of practical problems such as allocation time and algorithm fail in decision making. According to the numerical results, the proposed thrust allocation algorithm was more efficient than the conventional ones. Thus including operational data to models we can improve its work and make it more reliable.*

***Keywords**: Algorithm, Thrust-allocation, interference, DP System.*

1. INTRODUCTION

1.1. Dynamic Positioning (DP) System

The DP System is a new technology that is being implemented nowadays for offshore operations. It an alternative for the conventional mooring system. This technology should experience vigorous growth due to the oil discoveries in the Pré-Sal area in the Brazilian coast.

The main objective of the DP system is to maintain the ship position allowing the vessel to perform the offshore operations, such as, offshore drilling, offloading, and others. To perform its function the DP system has different tasks, shown in Fig. 1. More details of the DP System can be found in De Wit 2009, Tannuri 2001 and Tannuri 2002.

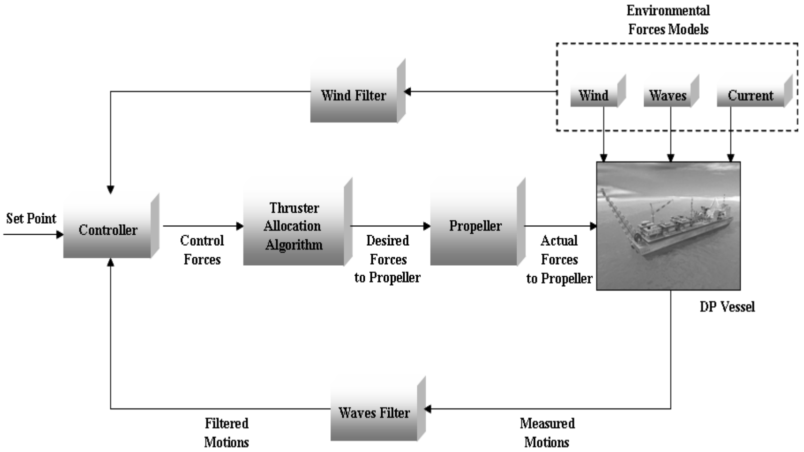

Figure 1: Block diagram of a DP System.

As shown by the figure above, the DP System is a feedback control system that maintains the vessel stationary on a desired location. One of the most important functions of the DP system is the Thrust Allocation, which is calculating the thrust and working position of the vessel thrusters to balance the Environmental Loads. Some strategies were studied to optimize the thrust allocation (De Wit 2009, Moberg and Hellstrom 1983, and Tannuri 2001), and the present work will suggest a new one, and compare with the conventional thrust allocation algorithm.

Although the DP System presents feedback, it does not consider the efficiency reduction of the thrusters due to the interference phenomena. Therefore how can we expect that the information calculated by the Thrust Allocation Algorithm is reliable? This work presents a Thrust Allocation Algorithm that considers the interference between thrusters and thrust-hull, which make the system more reliable and allow the improvement in terms of fuel consumption of the DP system.

Using environmental information and force models, it is possible to simulate the operation of DP system allowing the study for the optimization of the Thrust Allocation Algorithm. Next, the different types of thrusters that can be deployed by the DP system.

1.2. Qualitative Thruster Study

Before we study the interference between thrusters and thrust-hull, it is necessary to present some of the usual coordinates used when we work with naval projects. Figure 2 exemplifies the coordinate change done on those projects.

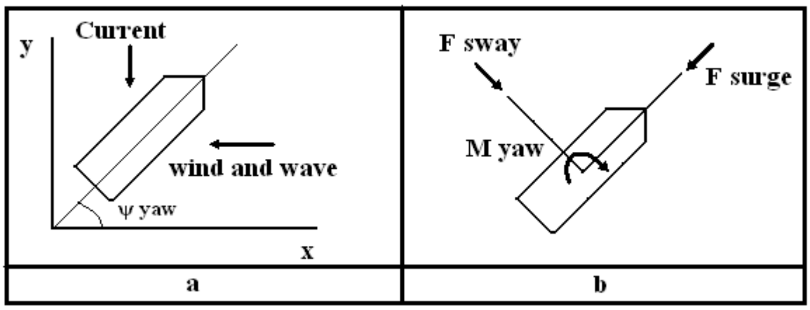

Figure 2: Coordinate transformation. From global coordinates (a) to the vessel coordinates (b).

DP vessels have three kinds of thrusters. Fig. 3a shows a main propeller; Fig. 3b a tunnel thruster; Fig. 3c an azimuth thruster.

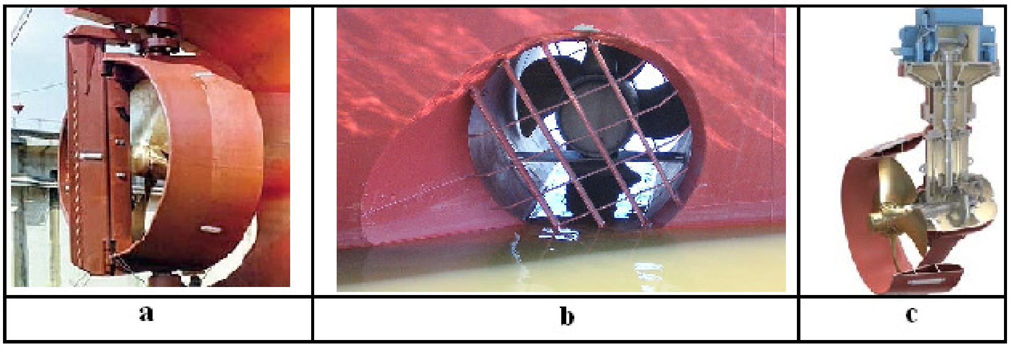

Figure 3: Types of thrusters of DP vessels.

Although the main propeller is not simulated in this work, it is easy to understand the effect of the interference over it. When the propeller produces force forward, it generates a water jet backwards, which flows freely to the sea. But when the main propeller produces force backwards, it generates a water jet that goes forward dragging to the hull of the vessel, decreasing the liquid thrust. Figure 4a shows the usual representation of the main propeller and Fig 4b the representation considering the interference phenomena.

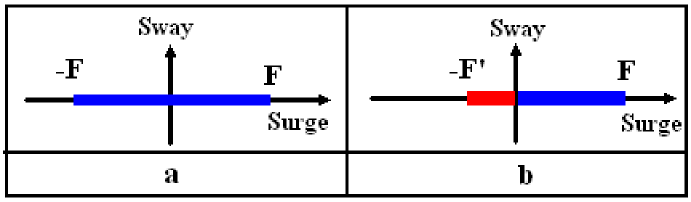

Figure 4: Main propeller representation. Standard representation (a). Suggested representation (b).

The tunnel thruster representation is similar to the main propeller. The differences are: it generates thrust in the Sway direction, and the liquid thrust is smaller in both ways, because the water jet drags along the tunnel.

The Azimuth thruster is the most representative when we evaluate both kinds of interference (between thrusters and thrust-hull). Therefore the simulations only consider this kind of thruster. Figure 5 shows how the interference between the water jet and other parts of the ship affects the effective thrust. Figure 5a is the ideal thrust. Figure 5b is an experiment to evaluate interference. It was done on a vessel different from the one simulated on this work, only to verify decrease of efficiency when the water jet of one thruster hits another, what happens at 240º.

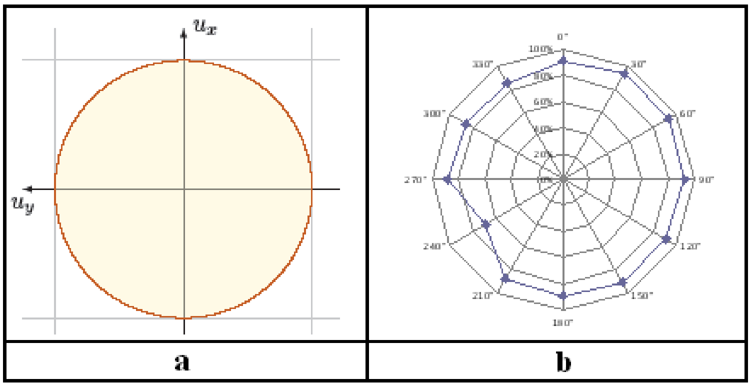

Figure 5: Azimuth thruster representation. (a) Standard representation in polar coordinates without interference (De Wit, 2009). (b) Suggested representation, in polar coordinates (efficiency test conducted to validate the model).

2. SUGGESTED THRUST ALLOCATION ALGORITHM

2.1. Case Study Vessel

Before the algorithm is introduced, a vessel (object of the suggested algorithm case study) is presented, therefore the explanation of the algorithm is exemplified based on the vessel, and its comprehension becomes easier. Following, the schematic of the vessel including thrusters' positions. Note that each thruster can generate 680 kN, consuming 4 MW.

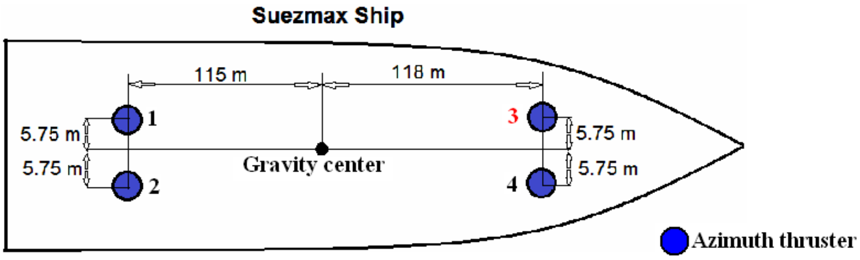

Figure 6: Ship schematic.

2.2. Mathematical treatment for thrust curve

To implement the interference data in the algorithm, different efficiency factors were considered, for each thrust angle for azimuth thrusters. Table 2 and Fig. 7b exemplify the approach to this problem. We considered two interference effects.

1) Between thrusters, this is shown by Fig. 7b. This data is from Moberg and Hellstrom, 1983, that simulated repeatedly the effects of the water jet of one thruster over a second one.
2) Thrust-hull: loss of 20 % of efficiency, when the water jet travels the whole hull (0º for thruster 3), and no losses when the water is lateral, 90º or 270º for thruster 3 for example. (Moberg and Hellstrom, 1983).

Note that both kinds of interference can happen at the same time, and their private effects are added.

Table 1: Efficiency factors for thruster 3.

angle [º]	efficiency	angle [º]	effic	angle [º]	effic	angle [º]	effic
0	0,80	50	0,91	100	0,75	310	0,91
10	0,82	60	0,93	110 - 270	1,00	320	0,89
20	0,84	70	0,96	280	0,98	330	0,87
30	0,87	80	0,75	290	0,96	340	0,84
40	0,89	90	0,50	300	0,93	350	0,82

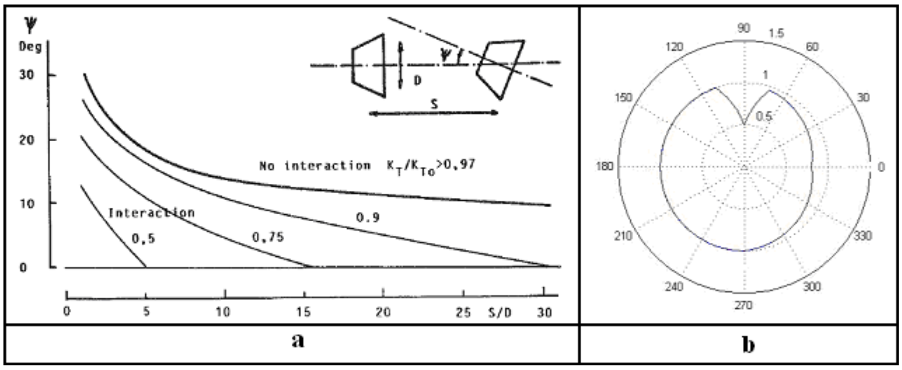

Figure 7: (a) Thruster-Thruster interaction (Moberg and Hellstrom, 1983). (b) Thruster 3 efficiency in polar coordinates.

2.3. Suggested Algorithm Structure

The structure of the allocation program developed is presented in the Fig. 8.

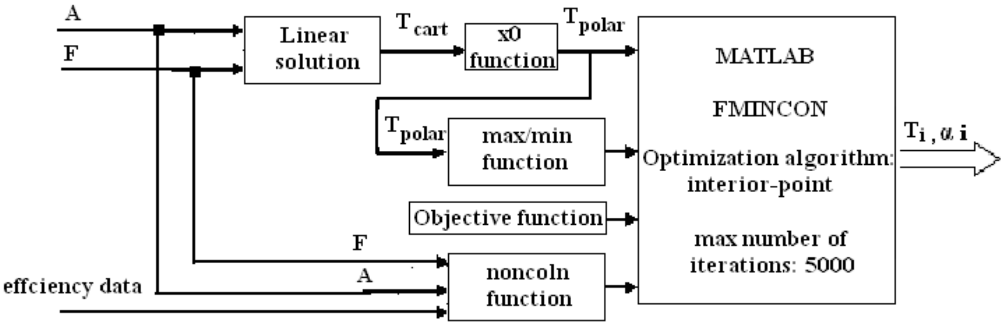

Figure 8: Block diagram for Thruster Allocation Algorithm.

- **Matrix A**

Matrix A is the corresponding representation to the thrust generated by each thruster. First line is Surge direction; second line is Sway direction and third line is moment. Azimuth thrusters are represented for two columns because they can generate thrust both in Surge and Sway Directions, as shown in the matrix below. In the first column there is thrust in the Surge direction and momentum depending of its lateral position (*Y*). The second column shows its contribution in the Sway direction, note that it can also generate momentum depending of its longitudinal position (*X*)

$$\mathbf{A} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -\mathrm{Y} & \mathrm{X} \end{bmatrix} \tag{1}$$

For main propellers and tunnel thruster you may see De Wit, 2009.

- **Vectors F , $\mathbf{T_{cart}}$ and $\mathbf{T_{polar}}$**

Vector F contains the environmental loads over the ship.

$$\mathbf{F} = \begin{bmatrix} Fsurge \\ Fsway \\ Myaw \end{bmatrix} \tag{2}$$

T_{cart} has the allocation solution in Cartesian coordinates; and T_{polar} has the solution in polar coordinates.

$$\mathbf{T_{cart}} = \begin{bmatrix} \mathrm{Fsurge} \\ \mathrm{Fsway} \end{bmatrix} \tag{3}$$

$$\mathbf{T_{polar}} = \begin{bmatrix} T_{(\,thrust\,)} \\ \alpha_{(\,direction\,)} \end{bmatrix} \tag{4}$$

- **Linear Solution**

This function solves the problem of allocation regardless of the interference problem. It is the initial guess necessary for the optimization algorithm. Note that pinv is the pseudo inverse of a matrix.

$$\mathbf{T_{cart}} = \text{pinv}(\mathbf{A}) \times \mathbf{F} \tag{5}$$

The solution T_{cart} found is an allocation for the minimum fuel considering the relation in Eq. 6 (Sordalen, 1997). This relation is similar to the correct one, which will be presented in the objective function (Eq. 13), but this allocation is a good initial guess. Note that *n* is the number of thrusters.

$$\text{Power} = \sum_{i=1}^{n} (\text{Thrust}_i)^2 \tag{6}$$

- **x0 function**

This function transforms the linear solution T_{cart} into polar coordinates T_{polar}. To exemplify it, this function receives Surge and Sway Forces of the same azimuth thruster ($T_{cart}(1)$ and $T_{cart}(2)$ respectively), and provides the modulus of the thrust $T_{polar}(1)$, and the propulsion angle $T_{polar}(2)$.

- **max/min function or problem restrictions**

This function shown in Eq. 7 provides the restriction of the thrusters, which means, the maximum and minimum thrust and propulsion angle for each thruster. Note that the maximum allowable thrust [N] represents only 80% of the maximum thrust, keeping 20% of safety margin (Moberg and Hellstrom, 1983).

$$\begin{aligned} 0 &\le T_i \le 0{,}8 \cdot T\max \\ 0 &\le \alpha_i \le 2\pi \end{aligned} \tag{7}$$

- **Objective Function**

The objective function relates the power consumed with the thrust (T) exercised. This relation is shown in Eq. 8 (Tannuri 2002). The objective function is the core in the solution of an optimization problem. Therefore the algorithm should minimize the Objective function, which would save fuel, and power.

$$\text{Power} = \lambda T^{\frac{3}{2}} \tag{8}$$

Note that λ is a constant value equal for all the thrusters. Therefore it does not affect the objective function. The objective function represented in Eq. 9 depends only of the exercised thrust.

$$\text{Objective Function} = \sum_{i=1}^{n} (T_i)^{\frac{3}{2}} \tag{9}$$

- **Efficiency data (*effic*)**

effic is the efficiency data, as explained in item 2.1, for each thruster. Figure 7b exemplifies the efficiency for thruster nº 3 of the case study vessel. To obtain the data for this function you must perform experiments in each thruster, without the feedback, and measure the liquid thrust. The relation between the measured thrust and the commanded one will provide the efficiency of the thruster.

- **noncoln function**

The nonlinear constrained function (Matlab handbook, 2008) guarantees station keeping of the vessel. This system represents the three equilibrium equations of the ship (Surge and Sway directions, and moment; Eq. 10), considering the interference problem, therefore, the algorithm should solve this system saving as much fuel as possible, which is the same as minimizing the objective function.

$$\begin{cases} \sum_{i=1}^{n} T_i \, cos(\alpha_i).effic_i(\alpha_i) - Fsurge = 0 \\ \sum_{i=1}^{n} T_i \, sin(\alpha_i).effic_i(\alpha_i) - Fsway = 0 \\ \sum_{i=1}^{n} T_i effic_i(\alpha_i).[X_i \, sin(\alpha_i) - Y_i \, cos(\alpha_i)] - Myaw = 0 \end{cases} \tag{10}$$

- **fmincon** (Matlab handbook, 2008)

The algorithm is performed by the program Matlab, and fmincon function, which solves the equilibrium system, seeking for the minimum of the objective function. An important option is the optimization algorithm: *interior-point*. If the system admits no solution (the environmental loads are too high for the vessel), the moment is balanced, thus if the vessel cannot stay still, it does not rotates (it is favorable decision making for the developed algorithm). Also, 0.6 s is the maximum time for allocations.

3. RESULTS

3.1. Simulation methodology

The simulation program developed to evaluate the DP operation of the vessel, considers three different approaches to the station keeping problem, thus three different algorithms.

1) Suggested algorithm (considering the interference between thrusters and thrust-hull);
2) A feedback allocation algorithm with forbidden zones (20° around the angle that the thrusters water jet hits another thruster), normally used on ships;
3) A simple feedback allocation ($pinv(A)$), algorithm using only Eq. 6 for power consumption, normally used on capability plot simulations.

The feedback simulations guarantee that the ship will balance the environmental loads. Since the forbidden zone algorithm (2), and the feedback allocation algorithm (3) does not have the function *effic* the first allocation will not equalize the forces over the ship. So we simulate a feedback control loop, correcting the force to be allocated, by means of this block diagram, Fig. 9:

Figure 9: Feedback simulation block diagram.

3.2. Calculation of environmental loads

3.2.1. Current forces

The current force for static conditions is calculated through the formulas Eq. 11 (Tannuri, 2002). The dimensionless factors C_{ci} for the current loads over the ship depend on the incident angle θ of the current on the vessel. Those factors can be determined by experimental tests, or by computer simulations of the design of the ship hull.

As we would expect the current forces depends on the water density (ρ_{water}); the vessel length (L); the ship draft (D); the dimensionless factors (C_{ci}) for surge, sway and yaw directions; and the current velocity (U).

$$\begin{cases} Fsurge = \frac{1}{2} \rho_{water} L D C_{c1}(\theta) U^2 \\ Fsway = \frac{1}{2} \rho_{water} L D C_{c2}(\theta) U^2 \\ Myaw = \frac{1}{2} \rho_{water} L^2 D C_{c3}(\theta) U^2 \end{cases} \tag{11}$$

3.2.2. Wind forces

The wind forces over the vessel, Eq. 12, can be evaluated with similar expressions to the current forces, because both are fluid flow phenomena. The wind forces depend on the air density (ρ_{air}); the significant area for the air drag (frontal A_f , or lateral A_l); another dimensionless factor (C_{wi}) that depends on the attack angle of the wind (γ); the wind velocity (V); and the ship length (L) for the moment longitudinal distance.

$$\begin{cases} Fsurge = \frac{1}{2}\rho_{air} A_f C_{w1}(\gamma) V^2 \\ Fsway = \frac{1}{2}\rho_{air} A_l C_{w2}(\gamma) V^2 \\ Myaw = \frac{1}{2}\rho_{air} A_l L C_{w3}(\gamma) V^2 \end{cases} \tag{12}$$

3.2.3. Wave forces

To estimate the forces over the vessel we used the methodology described in Tannuri, 2002. Those forces are the result of the wave spectrum, and the frequency of it. The model developed by Pierson-Moskowitz was simulated for this class of forces.

Also, there are forces due to the interaction between waves and current. Explaining the methodology to estimate the loads of irregular waves would take too long, but the important parameters to determine them will be presented: wave significant high (Hs), wave period (Tp), wave and wind incident angle (γ), current velocity (U), current angle (θ) and dimensionless coefficients $C_{oi}(Tp, \gamma)$.

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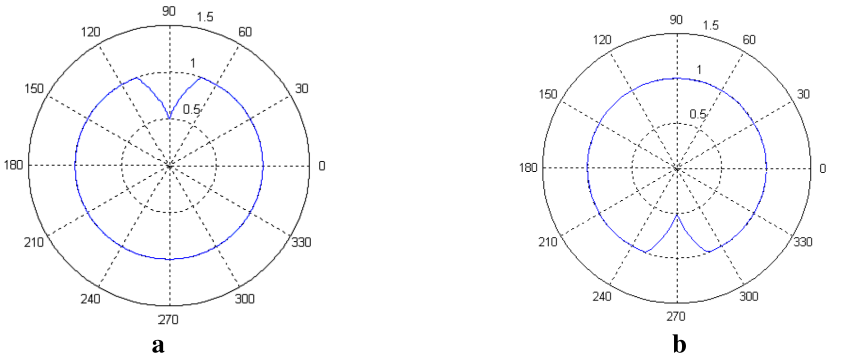
3.3. Forbidden zone analysis

Initially we will evaluate whether is beneficial to enter the forbidden zone, only considering the interference between thrusters. Note that thrusters 1 and 3 have the same configuration as shown in Fig. 10a; and thrusters 2 and 4 have the efficiency shown in Fig. 10b.



a **b**

Figure 10: (a) Efficiency of thrusters 1 and 3 considering only the interference between thrusters. (b) Efficiency of thrusters 2 and 4 considering only the interference between thrusters.

Based on the Fig. 11 it is easy to observe that there is no advantage entering the forbidden zone, when we consider only the interaction between thrusters. Figure 11a represents the final results either for the suggested algorithm (1) or for the forbidden zones algorithm (2). Figure 11b shows the final result for the simple feedback allocation algorithm (3). It takes 43% more power to reach the equilibrium (guaranteed by the feedback) within the forbidden zone. This example shows that if only the thruster-thruster interaction is considered, the algorithms 1 and 2 are equivalent.

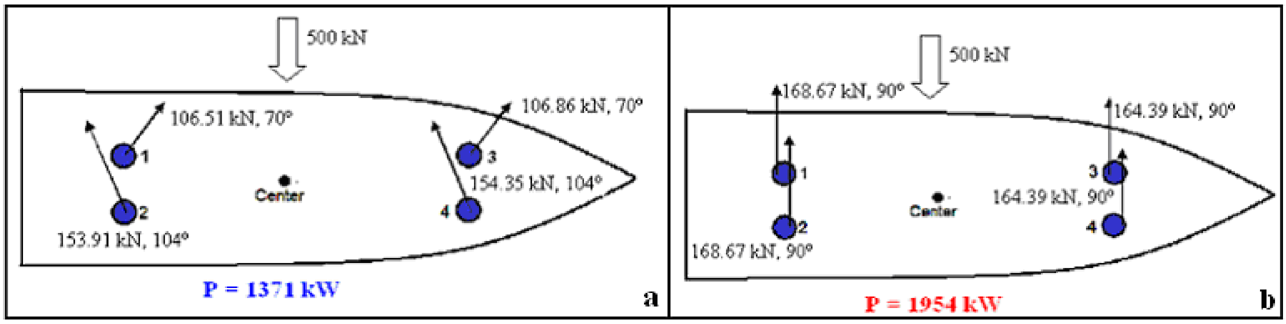


Figure 11: (a) Result allocation for algorithms 1 and 2 according to the forces over the ship. (b) Final thrust allocation of algorithm 3.

3.4. Complete simulation

Now the ship behavior will be simulated when we consider the interference between thrusters and thruster-hull. Fig 12 shows the efficiency of the four thrusters of the vessel considering both kinds of interference.

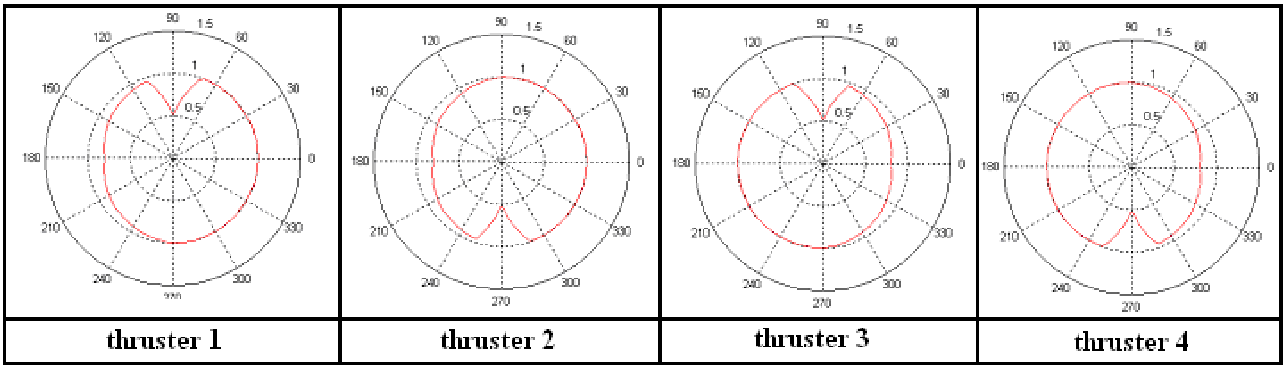


Figure 12: Efficiency of all 4 thrusters.

The simulation, shown in Fig. 13, considers the environmental loads reaching the ship at bow. The suggested algorithm (1) spends 2.5% less power to reach the equilibrium Fig. 13a, than the forbidden zone algorithm (2) or the simple feedback allocation (3), whose final results are equal, Fig. 13b.

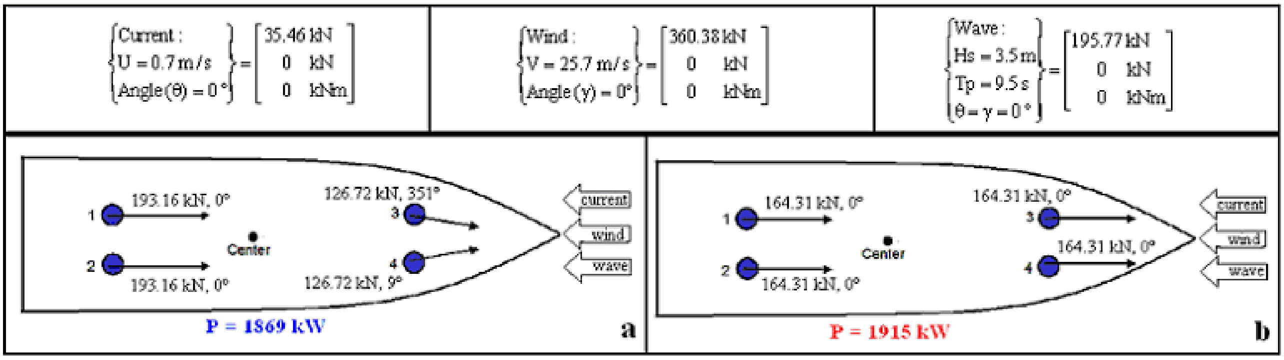


Figure 13: (a) Result allocation for algorithm 1 according to the forces over the ship. (b) Final thrust allocation of algorithm 2 and 3.

The next simulation represents the ship dealing only with Sway forces (500 kN), note that the forbidden zone algorithm (2) (Fig 14b) did not entered the forbidden zone and spent 0.5%, more power than the suggested algorithm (1) (Fig. 14a). Whereas the simple feedback allocation algorithm (3), not represented, positioned all thrusters at approximately 90º and spent 39.5% more power than the suggested algorithm, similar condition to Fig. 11b.

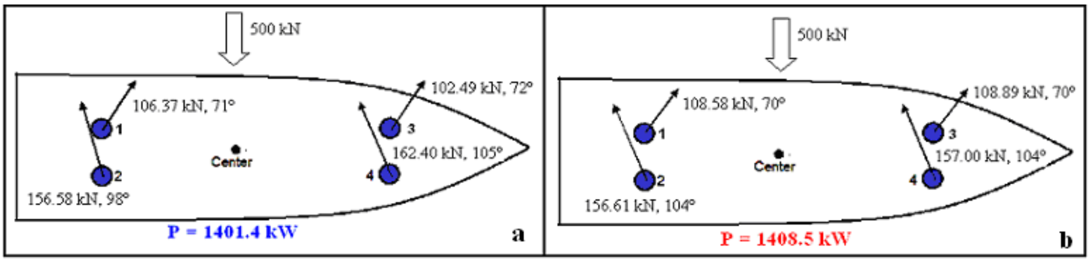


Figure 14: (a) Result allocation for algorithm (1) according to the forces over the ship. (b) Final thrust allocation of forbidden zone algorithm (2).

This example revealed the greater quality of the suggested algorithm: it can measure both kinds of interference (thruster-thruster and thrust-hull), and decide the best thruster allocation optimally and objectively.

A capability plot that is a radar graph that shows the estimated power or the maximum current, including constant wind and wave conditions, that the vessel can bear was simulated. The data was provided by PETROBRAS and the percentage of power consumed is shown in Fig 15.

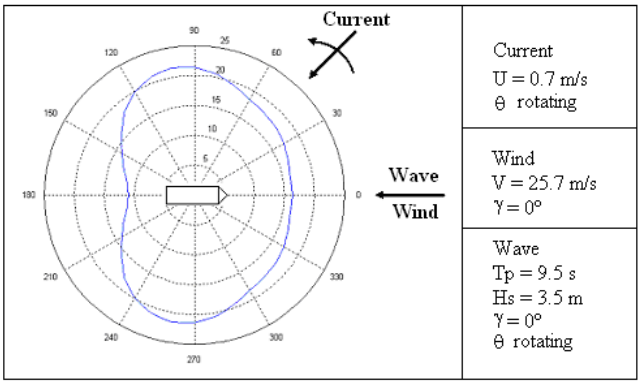


Figure 15: Capability plot of power, for the suggested algorithm.

This capability plot was simulated for the other two algorithms. Table 2 shows the comparison between them. According to the data, it can be noticed the advantage of the suggested algorithm.

Table 2: Comparison of algorithms trough the capability plot.

Algorithm	Mean-Maximum extra power in relation to the suggested algorithm	Mean allocation time
Suggested Algorithm (1)	-	0.39 s
Forbidden zones (2)	1.5% - 2.5%	0.26 s
Feedback allocation (3)	3% - 5.5%	4.10^{-5} s

Another condition was considered, shown in Fig. 16, with increasing current. Through the tests we determined the maximum current that the ship could bear (1.35 m/s, marked by an arrow in Fig 14 right). Figure 14 left, show the environmental forces increasing combined with the current. Figure 14 right, illustrate the thrusters efforts to balance the environmental conditions.

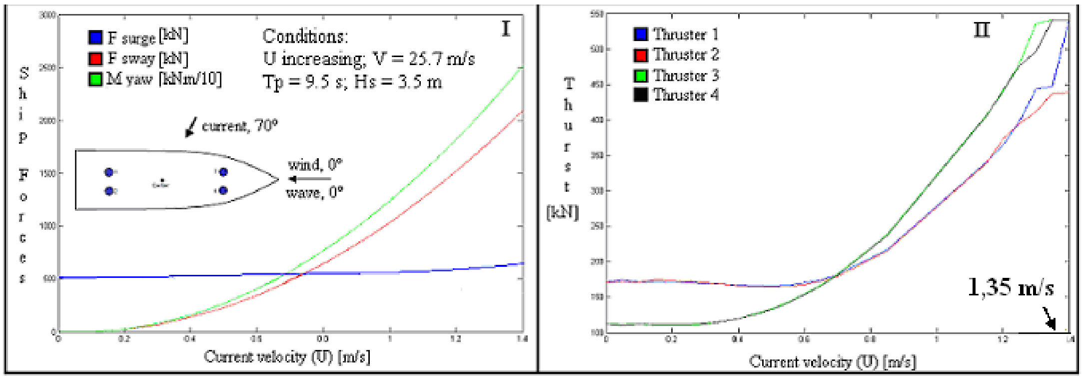


Figure 16: Environmental forces growing with the current; Thrusters efforts to balance weather conditions.

4. CONCLUSIONS

The experimental data for interference simulations is very similar to the bibliography data; therefore it is reasonable to define efficiency functions for each propeller according to its angle, as was made in the present work.

Although the allocation time of the suggested algorithm is higher than the other algorithms, the vessel time scale phenomena are much bigger than the maximum execution time (0.6 s), thus the suggested algorithm can be implemented on ships without causing any problem regarding execution time.

If the vessel operates in a weathervane mode (alignment to the environmental condition), the simulations have indicated a power economy of approximately 2.5 %, Fig. 13. This is very significant, since vessels with DP System can work continuously for up to 36 h. The proposed thruster allocation algorithm could be implemented without major modifications in the DP system.

A simple count considering the energy of 1 L of diesel equals to 10,000 Kcal (41800 KJ). Burn efficiency equals to 30%. Supposing 36 h of continuous work for the conditions simulated at Fig. 13 (46 kW saved). Also supposing 10 ships with the suggested algorithm implemented. And the vessels operate once, every 2 weeks.

$$\text{Energy Saved} = 46 \cdot 10^3\ \text{W} \cdot 36\,\text{h} = 6.10^9\ \text{J/ operation} \tag{13}$$

$$\text{Fuel Saved per operation} = \frac{6.10^9\ \text{J}}{41800 \cdot 10^3 \cdot 0.3\,\text{J/L}} = \frac{478\,\text{L}}{\text{operation}} \tag{14}$$

$$\text{Fuel Saved per year} = \frac{478\,\text{L}}{\text{operation}} . \frac{26\,\text{operations}}{\text{Ship (1 year)}} \cdot 10\,\text{ships} = \frac{129 \cdot 10^3\ \text{L}}{\text{year}} \tag{15}$$

Since the price of the fuel is very volatile any prediction of money saved would be inaccurate.

Another important contribution of the work is that it is an optimization method that considers all interference effects during the allocation of thrust. It can also be applied during the design stage, for time domain simulations or capability plot calculation.

5. ACKNOWLEDGEMENTS5

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