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Ship Science & Technology is a specialized journal in topics related to naval architecture, ship design, hydrodynamics, dynamics of ships, structures and materials, vibrations and noise, technology of ship construction, ocean and marine engineering, standards and regulations, oceanography, maritime and river transport, and port infrastructure. Every six months, the journal publishes scientific papers that constitute an original contribution in the development of the mentioned areas, resulting from research projects of the Science and Technology Corporation for the Naval, Maritime and Riverine Industries, and other institutions and researchers. It is distributed nationally and internationally on paper and online.

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Editorial Note

Cartagena de Indias, January 30th, 2022.

I want to start this new edition of our Ships Science and Technology Journal, with our wishes to all our authors, readers, and members of the editorial board, so that this year 2022 will be full of personal and professional successes. Thank you all for your valuable contributions to our Journal.

We closed a year 2021 full of the challenges imposed on world society by the COVID 19 pandemic, but we managed to successfully carry out with the support of the scientific community our VII International Ship Design and Naval Engineering Congress CIDIN 2021, an event that through the virtual modality, It continued to consolidate itself as the main academic -scientific space for technology and knowledge transfer for the strengthening of the naval, maritime and river industries. Our acknowledgments to all the panelists, speakers and organizing team for this successful event.

In this edition of the Journal we will cover topics such as: Numerical simulation of a SEA Arrow Bow; Electromechanical model of a based catamaran vessel; Latam Shipbuilding Competitiveness; How to improve the shipbuilding industry with the Internet of ships concept; and Shallow Water Resistance Estimation for a Riverine Light Patrol Boat using Computational Fluid Dynamics, which we hope will be a contribution to the consolidation of knowledge in the industry.

Happy 2022 everyone

Cordially,

Captain (ret.) CARLOS EDUARDO GIL DE LOS RÍOS
Ship Science and Technology Journal Editor

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Nota Editorial

Cartagena de Indias, 30 de enero de 2022

Quiero iniciar esta nueva edición de nuestra revista Ciencia y Tecnología de Buques, con nuestros deseos a todos nuestros autores, lectores y miembros del consejo editorial, para que este año 2022 sea lleno de éxitos personales y profesiones. Gracias a todos por sus valiosos aportes a nuestra revista.

Cerramos un 2021 lleno de los retos impuestos a la sociedad mundial por la pandemia de la COVID 19, pero logramos realizar exitosamente con el apoyo de la comunidad científica nuestro VII Congreso Internacional de Diseño e Ingeniería Naval CIDIN 2021, evento que, mediante la modalidad virtual, se siguió consolidando como el principal espacio académico-científico de transferencia tecnológica y del conocimiento para el fortalecimiento de la industria naval, marítima y fluvial. Nuestros reconocimientos a todos los panelistas, ponentes y equipo organizador por este exitoso evento.

En esta edición de la revista tocaremos temas como: Simulación numérica de una proa SEA Arrow para una embarcación pesquera; modelo electromecánico de una embarcación tipo catamarán; competitividad de la industria naval latinoamericana; como mejorar la construcción naval con el concepto de Internet of Ships; y Estimación de la Resistencia al avance en aguas poco profundas para un Bote de Combate Fluvial de bajo calado mediante Dinámica Computacional de Fluidos, los cuales esperamos sean de su interés y aporte a la consolidación de conocimiento en la industria.

Feliz 2022 a todos.

Cordialmente,

Capitán de Navío (RA) CARLOS EDUARDO GIL DE LOS RÍOS
Editor revista Ciencia y Tecnología de Buques

Numerical simulation of a SEA Arrow Bow for a fishing vessel

Simulación numérica de una proa SEA Arrow para una embarcación pesquera

DOI: https://doi.org/10.25043/19098642.224

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Abstract

The hull designs of the Peruvian fishing fleet lack hydrodynamic studies, which is why, in the present work, a study of the resistance to the advance of a classical model of the type mentioned, called "MMS", is carried out. An experimental numerical correlation is carried out with this model to validate the proposed methodology.

The numerical methodology uses CFD using Ansys-Fluent software, considering turbulent behaviour for a multiphase fluid (water-air), a mesh with inflation layers and refinements, among other characteristics. The results show a maximum error of 5% in relation to the results obtained experimentally. Based on this methodology, the behaviour of the adaptation of a SEA Arrow type bow to the MMS model is analysed. The results of this new proposal consider a decrease of up to 10% in the total resistance at different operating speeds.

Key words: Fishing vessel, CFD, SEA-Arrow Bow.

Resumen

Los diseños de casco de la flota pesquera peruana carecen de estudios hidrodinámicos, es por eso que, en el presente trabajo se realiza un estudio de resistencia al avance de un modelo clásico del tipo mencionado denominado "MMS". Con dicho modelo se realiza una correlación numérica experimental para validar la metodología propuesta.

La metodología numérica utiliza CFD mediante el software Ansys-Fluent, considerando un comportamiento turbulento para un fluido multifásico (agua- aire), una malla con capas de inflación y refinamientos, entre otras características. Los resultados muestran un 5% de error máximo en relación a los resultados obtenidos experimentalmente. A partir de esta metodología es analizado el comportamiento de la adaptación de una proa tipo *SEA Arrow*, al modelo MMS. Los resultados de esta nueva propuesta, consideran una disminución de hasta 10% en la resistencia total a diferentes velocidades de operación.

Palabras claves: Embarcación pesquera, CFD, Proa SEA-Arrow.

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Introduction

Peru and, in general, traditional fishing countries recognize that their marine resources are a great source of income, making fishing one of the most important activities for their economy. For this reason, this sector is currently focusing its efforts on improving the performance of its operations to generate a higher profit margin.

Most industrial companies have experienced a growth in their fleet of vessels, however, it is observed that the new vessels have designs without specialized technical support, and in many cases building hulls based on standard models with slight modifications at the request of the owner.

Perhaps, one of the biggest unknowns of these designs is the use of a bow bulb, which is favorable only for some operating situations. In the case of fishing vessels, it is different, since they experience different operations during their navigation, making their draft vary in a very wide range.

The SEA Arrow bow was designed by the Japanese to be applied in LPG carriers, making them more energy efficient compared to their bulb and rounded bow version.

For its study, the design of an adaptation of the SEA-Arrow bow on the Marco Marine Seatlle model, which is a very common hull in industrial fishing vessels of the purse seine type, is taken. A CFD (Computational Fluids Dynamics) analysis is carried out for the forward resistance study, however, in the process it is shown that working with straight and very thin bows brings some extra difficulties that will be developed and solved in this research work.

Based on the recommendations issued by ITTC, a methodology is developed for a numerical analysis to determine the drag of a fishing vessel with a SEA-Arrow bow.

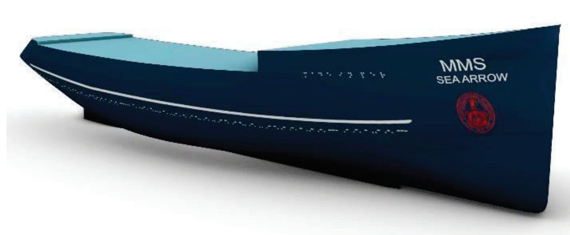
Study Model

The present research work takes as object of study the Marco Marine Seattle (MMS) ship model with a bow modification adopting the SEA-Arrow type bow (Sharp Entrance Angle bow as an Arrow). The model based on the MMS model is used in the coasts of Peru by companies dedicated to industrial fishing, having this vessel as part of their fleet of purse seine fishing vessels.

The SEA-Arrow bow was developed by Kawasaki Shipbuilding to improve the performance of medium speed vessels such as LPG carriers. This design achieves reduced drag by reducing the power requirement of the main engine by 6-10% compared to the bulbous model with a rounded bow, while maintaining the same volume.

The design of the MMS ship with SEA-Arrow bow was developed following the same principles as the SEA-Arrow bow developed by the Japanese. The model has a straight bow drawn from the most extreme point of the bow of the original bulbous model, which generates a longer waterline length, but maintaining its displacement in the maximum load condition. The study vessel is shown in Fig. 1.

Fig. 1. Isometric view of MMS SEA Arrow ship.



The MMS SEA Arrow model has a length of 44.7 m, which works with a draft of 4.5 m, resulting in a waterline length of 44.5 m. The main characteristics of the MMS SEA Arrow model are described in Table 1.

Table 1. Geometric characteristics of the fuel rod [1].

Main Characteristics	MMS SEA Arrow	Unit
Length overall	44.7	m
Length of waterline	44.5	m
Beam	10.1	m
Draft	4.5	m
Displacement	930.477	m
Wet Surface	563.19	m

Numeral Modeling

Equations of Government

The MMS SEA Arrow model is analyzed by means of CFD (Computational Fluid Dynamics) to determine the drag generated when the vessel moves at a certain speed.

For the development of the CFD, the domain is discretized by means of a mesh, on which it will be analyzed by means of the volume of fluid (VOF) method, which is the most appropriate to simulate the interactions of air and water in the free surface, being able to measure the volume fractions in each cell. The volume fraction is governed by the following equation:

$$\frac{\partial a}{\partial t} + Ui\frac{\partial a}{\partial x_i} = 0 \tag{1}$$

CFD is solved using the RANS (Reynolds Average Navier- Stockes) equations, which use average velocities for a given time period instead of instantaneous values to describe the flow, which requires less computational resources compared to DNS (Direct Numerical Simulation). Its X component can be defined as:

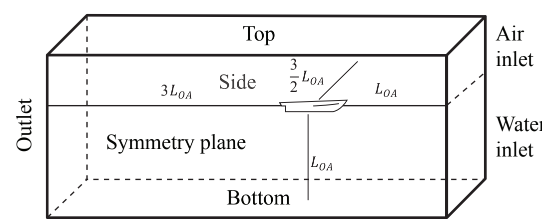
$$\rho\left(\frac{\partial \bar{u}}{\partial t} + u\frac{\partial \bar{u}}{\partial t} + v\frac{\partial \bar{u}}{\partial y} + w\frac{\partial \bar{u}}{\partial z}\right) = -\frac{\partial \bar{P}}{\partial x} + \mu\frac{\partial^2 \bar{u}}{\partial x^2} + \mu\frac{\partial^2 \bar{u}}{\partial y^2} + \mu\frac{\partial^2 \bar{u}}{\partial z^2} - \rho\frac{\partial \overline{u'u'}}{\partial x} - \rho\frac{\partial \overline{u'v'}}{\partial y} - \rho\frac{\partial \overline{u'w'}}{\partial z} + \rho g_x \tag{2}$$

To determine the drag force in a ship it is necessary to describe the turbulent viscosity in the RANS equations, for which turbulence models are employed, which use additional transport equations to describe the turbulent viscosity, allowing the turbulent velocity and length scales to be described independently. For the present investigation it has been decided to use the *k-ε* turbulence model, which allows to consider flow history effects such as convection and diffusion of turbulent energy.

Computational Domain

To perform the CFD analysis, the conditions of a hydrodynamic test channel are simulated using the recommendations given by the ITTC (International Towing Tank Conference). Fig. 2 shows the dimensions that the computational domain should have so that the waves reflected on the walls do not intervene in the calculation of the resistance.

Fig. 2. Dimensions that the computational domain.



Mesh

For the discretization of the domain, the Ansys environment was used to take advantage of its tools to generate the mesh. A meshing with a higher density of elements in regions of interest was performed to better capture the flow phenomena in the simulation. In addition, prism layers were created on the hull surface to resolve the boundary layer and obtain the shear stresses on the hull surface. The meshing was generated with the Cutcell meshing algorithm, which forms hexahedral elements, which has an approach adapted for a finite volume based solver. Fig. 3 shows an isometric view of the mesh in Ansys software.

Fig. 3. Isometric view of the mesh.

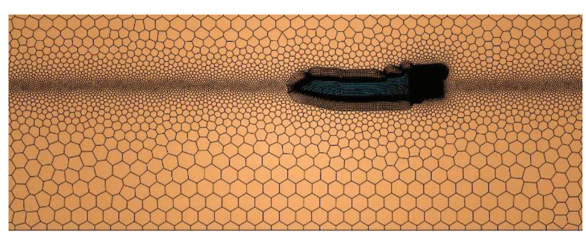
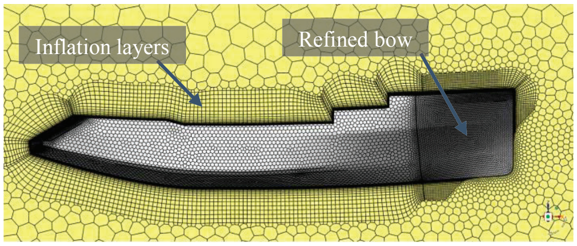


Fig. 4. Front view of the mesh.



Boundary Conditions

The boundary conditions are applied for the CFD numerical analysis, following the conditions of a towing test tank. Additionally, we work with only half, taking advantage of the symmetry property of the computational domain. Table 2 specifies the parameters that are used in the computational analysis for a specific speed, in the case shown is for 8 knots of speed.

Table 2. Boundary conditions for 8 knots.

Boundary	Type of boundary	Specification
Inlet	Pressure Inlet	8 knot – Parameter: Ship Velocity; Open Channel: Free Surface level: 0m Bottom level: 46m
Outlet	Pressure Outlet	Open Channel: Free Surface level: 0m Bottom level: 46 m
Top, side, bottom	Wall	
Symmetry Plane	Symmetry	
Hull	Wall	

Based on the indicated conditions, the equations are solved in Ansys Fluent

Results and Discussion

The three-dimensional model of the MMS model was subjected to CFD simulation, using the k-omega (2 eqn) viscosity model with second order solution methods. The simulation was performed to evaluate the drag at 5 velocity points in a range of 8 to 13 knots.

The run was performed with the most relevant operating speeds during the operation with vessels of this type, obtaining the resistance values shown in Table 3, where it is also presented a comparison with the results that can be found by Holtrop's method.

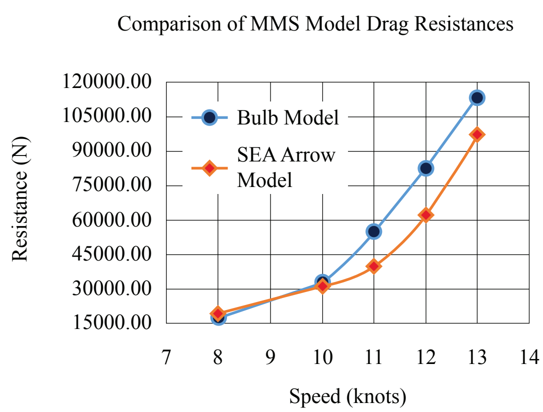
Table 3. Results of the ship's forward resistance MMS.

Velocity	Drag Force (Holtrop)	Drag Force (CFD)
8	19678.52	19,296.30
10	36995.88	31,230.12
11	52098.22	38,090.05
12	78724.57	62,415.55
13	102404.84	97,488.66

Table 3 reflects the wide margin of error of the Holtrop method, mainly in unusual vessel shapes, such as the SEA-Arrow bow analyzed in the present investigation. It should be noted that the higher the speed, the higher the percentage of error between the two methods.

Fig. 5 shows the trend of the exponentially sloping curve in accordance with the logic of the resistance generated by the vessels.

Fig. 5. Resistance vs. Speed of the MMS model.

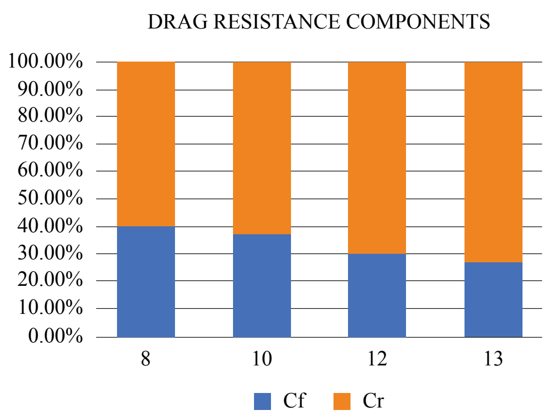


On the other hand, we have the data of the resistance to the advance of the model with bulb, for which we have that, for high speeds, the model with SEA Arrow bow presents resistance values lower by up to 25%, which results in an increase in speed of up to one knot.

It can be said that the resistance up to 11 knots maintains a not very pronounced trend, but from 11 knots on, the curve becomes more exponential. The cruising speed of the boat is approximately between 11 and 12 knots.

From the total resistance values, it can be broken down into frictional resistance and resistance due to wave formation. Fig. 6 shows the percentage of the frictional resistance and wave formation values with respect to the total resistance represented by 100%.

Fig. 6. Results of the ship's forward resistance MMS.



Likewise, Fig. 7 shows the waves generated by the original vessel with bow bulb at a speed of 12 kn.

In this figure, the first wave shows a high slope and a fast behavior that finally generates more waves. The opposite case is shown in Fig. 8, where the SEA-Arrow bow has a first wave with a much more subdued and delayed slope, which generates a smaller amount of waves than the bulbous bow.

Fig. 7. Wave profile generated by model with bow bulb.

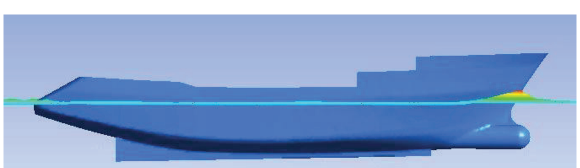
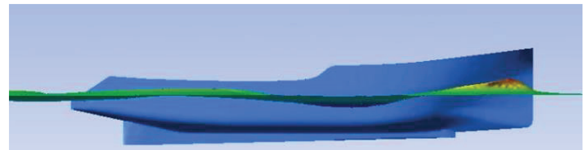


Fig. 8. Wave profile generated by the SEA Arrow bow model.



Conclusion

For the correct simulation of the phenomenon, the k-ε turbulence model was used, which satisfied the criteria to validate the simulation.

For the meshing of the vessels, the important parameters such as the size of the elements in the different regions, the layer of prisms around the hull surface were calculated complying with the recommendations given by the ITTC for these simulations.

The Holtrop empirical method presents an error in theresults of the ship resistance that varies between 8 and 35%.

ANSYS Fluent software was used to simulate these hulls of typical Peruvian vessels with the SEA ARROW bow to corroborate the reduction in drag, obtaining reductions of up to 25%.

Acknowledgments

To thank the National University of Engineering, for providing excellent teaching to its students, in order to apply their knowledge in the development and innovation of naval technology. In addition, to the DSc. Nain Ramos Alvarez, for the motivation and high-quality contribution, to achieve the advancement of both the naval engineering career, and the National University of Engineering.

Special thanks to the institute for development and research in naval engineering of the Faculty of Mechanical Engineering (IDIINFIM) of the National Engineering University (UNI), for allowing the use of its technological resources for the development of the paper.

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Electromechanical model of a based catamaran vessel

Modelo electromecánico de una embarcación tipo catamarán

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Abstract

The objective of this research is to provide a tool that allows to quantify the power requirements, energy consumption and the efficiency of the propulsion system of a catamaran with two degrees of freedom according to its speed. Furthermore, it seeks to improve the design process from a phenomenological perspective that gives rise to a better reliability of the result. To achieve this, an electromechanical model is being developed by using the methodology for obtaining phenomenological-based semi-physical models. This model couples the dynamics of a geometry-known ship with its propulsion system, which is constituted by a propeller and a brushless direct current (BLDC) electric motor; at the same time, it uses data from computational simulations related to the hydrodynamics of the submerged components. Finally, the results of using the model with parameters of a specific catamaran and motor are presented. This model allows to properly couple the dynamics of a boat with two degrees of freedom.
Key words: electromechanical model, catamaran, energy consumption, boat design, phenomenological modeling.

Resumen

El objetivo del trabajo es proporcionar una herramienta que permita cuantificar los requerimientos de potencia, consumo energético y eficiencia del sistema de propulsión de un catamarán con dos grados de libertad según su velocidad. Asimismo, se busca perfeccionar el proceso de diseño desde una perspectiva fenomenológica que dé lugar a una mayor confiabilidad del resultado. Para ello, se desarrolla un modelo electromecánico usando la metodología para la obtención de modelos semi físicos de base fenomenológica. Este modelo acopla la dinámica de una embarcación de geometría conocida con su sistema de propulsión, constituido por una hélice y un motor eléctrico de corriente continua sin escobillas (BLDC); a su vez, utiliza para su construcción datos provenientes de simulaciones computacionales referentes a la hidrodinámica de los componentes sumergidos. Finalmente, se presentan los resultados del modelo tomando parámetros de un catamarán y motor específicos. Este modelo permite acoplar de manera adecuada la dinámica de una embarcación con dos grados de libertad.
Palabras claves: modelo electromecánico, catamarán, consumo energético, diseño de embarcaciones, modelamiento fenomenológico.

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Introduction

Prediction and analysis of Hydrodynamic ship forces are important elements in naval design to determine the vessel hulls and their required propulsor. These forces allow to evaluate both water and air resistance to the ship's movement and to stablish the consequent propulsion system used to drive the craft [1]. However, resistance and propulsion are interdependent, and their phenomenological interaction behave as a coupled dynamical system. Achieving a system approach, given the objective to get an overall high efficiency of the vessel during its operation, represents an optimization problem [2]. This analysis is plenty complex for most naval architects, even with the current computational capacity [3]. To solve that, a systematic and iterative approach is chosen, as the spiral design process, where design is carried out step-by-step and the ship is split in different subsystems with established relations [3], [4]. This methodology reduces the required time in ship design but increases the later budget estimate for building and operation stage.

To compensate this effect, precise and efficient new methods, and models have been of interest in naval engineering and have been developed throughout the last years to improve design process. For example, dynamical models are well known tools that allow tracking physical phenomena during the ship's movement, which differ from common static models' scope that are used in design stages [5]. Thereby a dynamical model that accurately represents the physical interactions in a ship can be suitable to get corrective feedback in the subsystems design. As a result, it can improve their capacities, such as ship's energy efficiency, resistance, stability, and maneuvering [6]–[8]. And it can be used in the previous verification of the ship's requirements to achieve any possible reduction in building costs and a more reliable model's feedback for getting the final design.

Various authors have focused their efforts on the dynamic model development of different ships. The reviewed literature shows important improves for getting those models for naval designing and automatic control. The observed results on literature demonstrate a good approximation between the mathematical models and real data of the ship movement [9]–[11]. However, the coupling between the propulsion system and ship dynamics only has been studied in the last years. Some authors have considered the ship movement as load and focused on the modelling of the hybrid propulsion system. This approach avoids the use of ship dynamics and minimizes the motor dynamics [6], [12]. Other authors interpret the coupling between ship and propulsion as an input of the first over the second. For example, [13] models the load torque as a function of the propeller velocity coupled in the rotor propulsor. The most interesting approach is to considerer both dynamics and propose constitutive equations for guaranteeing a robust coupling on the model. Some modeled systems with this approach include coupling among synchronous machine, propeller, and hull [7] and coupling between mobile propulsor and the ship dynamics [5]. However, the current models do not include couplings between the hull dynamics and propulsion system based on brushless direct current motors (BLDC). In Addition, few articles considerer previous result of static models as input for the model development.

This paper proposes a coupled dynamic model constituted by the hydrodynamic forces involved in both ship resistance and propulsion, as well as their effects related to the power system behavior. In this way, it is developed a tool capable to measure the energy requirements by the ship throughout its entire operation. The methodology used in the present work is based phenomenological semi-physical modelling. It is feed by empirical formulations based on constitutive equations of the Process Systems (PS) added to a physical phenomenon developed with momentum balances [14]. Then, the results obtained can be included inside design process to improve ship efficiency. The paper is organized as: Process description is made based on the hull geometry and the motor properties of the vessel designed for testing the model. Detail level is described for getting requirements to achieve the model objective. Modeling Hypothesis are shown the physical and mathematical assumptions made according to the detail level. Process systems are developed conceptual stages of the whole system.

Governing equations are formulated based on the ship electromechanical behavior. Constitutive equations are derived from previous ones to stablish algebraic relations between subsystems. System's model is pointed out the differential equations that constitutes the model. Simulation is presented the results after running the model. Finally, conclusions are made, and future applications are mentioned.

Process Description

The vessel to model in this paper belongs to the catamaran category. These have two parallel hulls identical in size and geometry (Fig. 1). This architecture provides several advantages over traditional designs, like more stability. The catamaran to model has the following dimensions:

- Length: 5 m.
- Beam: 0.45 m.
- Depth: 0.53 m.
- Distance between hulls: 2.125 m.
- Total mass: 190 kg.

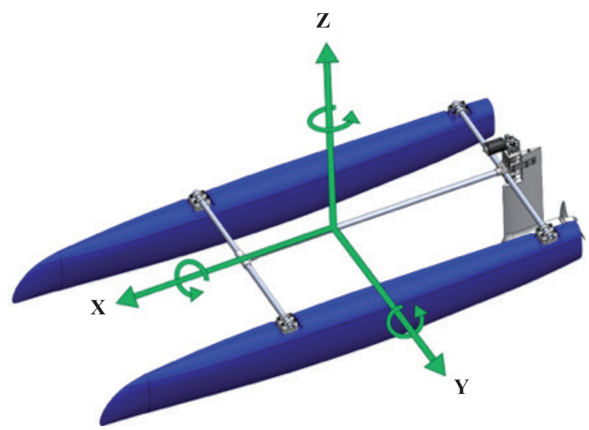
Additionally, it can reach a maximum speed of 5.6 m/s.

The catamaran is thrusted by a brushless DC motor of 5 kW power through a 48V supply. The main reasons why this motor is a good choice as a supply system are its high energy efficiency, high torque capacity and low torque variability when the revolutions per minute (RPM) are modified, compared to other motors like the Brushless AC [15]. In the shaft's motor, a 4 bladed propeller DTMB4148 is coupled, whose diameter is 30 cm, which provides the necessary thrust to move the vessel. Lastly, there is a rudder NACA 0018 of 60 cm length.

Detail Level

A vessel presents six degrees of freedom (DOF) in a three-dimensional system reference, three corresponding to linear motion and three to rotation (Fig. 1).

Fig. 1. Frame of reference in catamaran.



- Speed in X axis (Advance).
- Displacement in Z axis (heave).
- Average power needed in each instant of time.
- Energy consumption for a specific speed routine.
- Efficiency of system engine-propeller to different speeds.

Modeling Hypothesis

Fixed pitch: the pitch angle theta is fixed to a value which corresponds to the angular position of the boat at cruising speed. This angle is not variable, since we recreate the conditions, in which the drag measurements and the propeller performance curves were obtained. For this, the structural support is represented with two components: a spring with an associated force (FK) and a linear damper with dissipative force (FA).

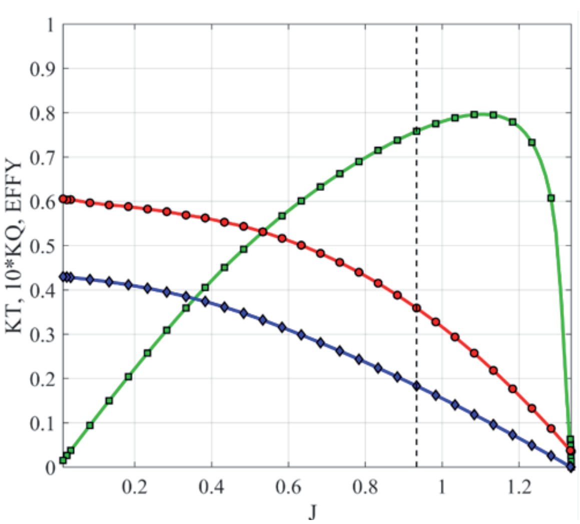
Simplified 2D model: the system moves along two linear directions in the XZ plane, since the other DOF are restricted by the structural support. This happens if it is assumed that the two hulls are moving symmetrically, thus it is not necessary to analyze each hull's motion independently.

Buoyant Force: The Buoyant Force (FB) is considered as the buoyancy over the group of submerged elements. It depends on the volume that the submerged body occupies, which varies according to the draft c. This draft c is a function of the z position.

Drag Force: the forces associated to drag in the whole submerged volume are the forces due to rudder drag (FAT) and due to hull drag (FAC), which are modeled as non-linear hydraulic dampers. FAT depends on the surge speed; on the other hand, FAC is a piecewise function composed by two sections, which depends on the surge speed as well as the draft.

Propulsion Force: propulsion force (FP) and propeller load torque (Tl), are considered as functions of the advance number (Js), that depends on the propeller angular velocity and the surge speed. The values (required) for these (from which the) regressions are obtained from the theoretical performance curves of the selected propeller (Fig. 2). In the figure, KT refers to the thrust coefficient, KQ to the torque coefficient and EFFY to the mechanical efficiency.

Fig. 2. Theoretical performance values of a propeller.



Added Mass: the added mass factor is quantified for the surge acceleration, considering the hull volume that interacts directly with the fluid as explained on [8].

Process Systems

These are the conceptual stages of the process that allow a better comprehension of the whole system. In general, there are two systems: mechanical and power system, each one with its respective subsystems.

Mechanical system: The boat hulls, the propulsion system and the rudder make up the mechanical system, these parts are the ones which interact directly with the water. In dynamic models of boats, two reference frames are found: one that is fixed to the boat located in its center of gravity (CG) and an earth-fixed frame aligned with the water level. In this model, there is a fixed angular position θ in between the two frames. This angle corresponds to the invariable trim of the catamaran.

Fig. 3a shows the general free body diagram without applying the hypothesis we already mentioned, the different subsystems of the mechanical system can be identified. However, for the general equations presented in this paper, a simplified free body diagram is used (Fig. 3b).

Power system: this system is integrated by a three-phase Brushless DC motor (BLDC) that divides the input voltage in a three-phase AC signal that feeds the three lines of the motor. Fig. 4 shows the equivalent circuit of this BLDC motor.

Fig. 3. a) Free body diagram of mechanic system without applying the modelling hypothesis. (b) Free body diagram of mechanic system applying the modelling hypothesis.

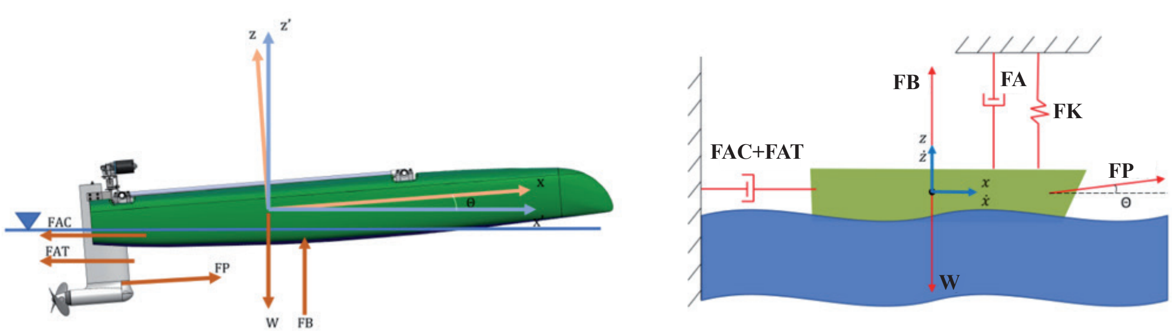


Fig. 4. Equivalent circuit of BLDC motor [16].

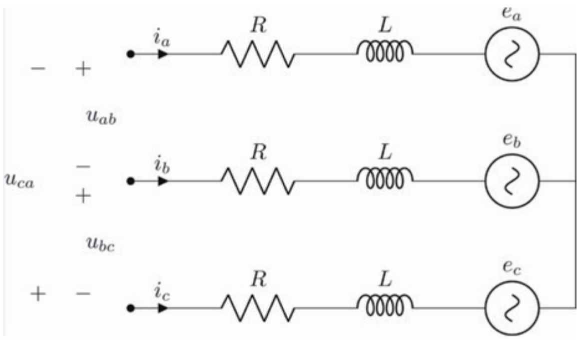


Fig. 5 and 6 illustrate the interaction between these systems. There is an input voltage applied to the motor to generate electric power and finally obtain position values in Z axis and velocities in X and Z. The variables that relate these two systems are: angular velocity and load torque that belongs to the rotational dynamic of the motor-propeller coupling.

Fig. 5. Block diagram of the system.

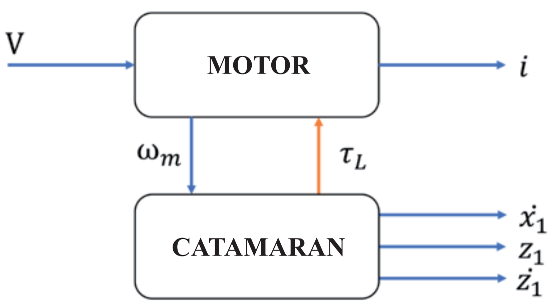
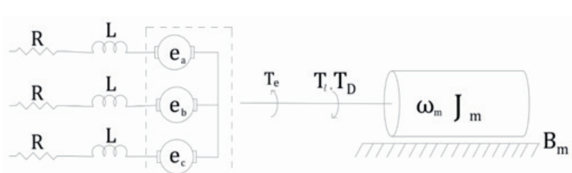


Fig. 6. Torque diagram.



Governing Equations

To obtain the equations that describe the electromechanical behavior of the vessel, the balances corresponding to each system have been made. Tables 1, 2 and 3 show the variables, parameters, and constants.

Table 1. Model Variables.

Variable	Units	Description
u_a y i_a	*V y A*	Line A voltage and current
u_b y i_b	*V y A*	Line B voltage and current
u_c y i_c	*V y A*	Line C voltage and current
θ_m	*rad*	Motor angle
ω_m	*rad/s*	Angular motor speed
u_{DC}	*V*	Input voltage
x_2	*m/s*	x-axis speed
z_1	*m*	z-axis position
z_2	*m/s*	z-axis speed

Table 2. Model Parameters.

Parameter	Value	Units	Description
L	4.22	*mH*	Armature Inductance [17]
R	0.7	*Ω*	Armature Resistance [17]
B_m	0.002	$N \cdot m \cdot s$	Damping constant [17]
k_{em}	0.8167	*V/(rad/s)*	Back-EMF constant [17]
k_{tm}	0.8167	$N \cdot m/A$	Electromagnetic torque constant [17]
J_m	0.0002	$kg \cdot m^2$	Motor's moment of inertia [17]
D	0.3	*m*	Propeller's diameter
θ	5	° *(degree)*	Angle between the velocity vector and the positive x-axis of the frame of reference
m	190	*kg*	Vessel's mass
k_{mass}	0.1	-	Added mass
K	1000	*N/m*	Spring constant of the structural support
B	150	$N \cdot s/m$	Damping constant of the structural support
w	0.2	-	Wake fraction factor

Table 3. Model constants.

Constant	Value	Units	Description
g	9.8	m/s^2	Gravity
ρ	1000	kg/m^3	Water density
γ	9800	N/m^3	Water specific weight

In the mechanical analysis the XZ plane of the vessel is considered, and Newton's second law is applied to describe the movement kinetics (Equations 1, 2 and 3). Notice that M, defined as $M = m(1+k_{mass})$, is the ship's total mass and includes the added mass.

$$M \begin{bmatrix} \dot{x}_2 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} \Sigma F_x \\ \Sigma F_z \end{bmatrix} \quad (1)$$

$$M\dot{x}_2 = FPcos\theta - FAC - FAT \quad (2)$$

$$M\dot{z}_2 = FPsin\theta - FK - W + FB - FA \quad (3)$$

Equations 4, 5, 6 show the result of applying Kirchhoff's voltage law to each line in the three-phase motor equivalent circuit (Fig. 4).

$$V_{La} = u_a - V_{Ra} - e_a \quad (4)$$

$$V_{Lb} = u_b - V_{Rb} - e_b \quad (5)$$

$$V_{Lc} = u_c - V_{Rc} - e_c \quad (6)$$

Finally, the coupling of electrical and mechanical systems can be modelled by following Newton's second law for rotational dynamics on the shaft where motor and propeller are placed (Equation 7).

$$J_m \dot{\omega}_m = \tau_e - \tau_l - \tau_D \quad (7)$$

Constitutive Equations

To find conclusive results from the governing equations, constitutive equations of the system's elements are introduced.

FP is a resultant force from a pressure field generated by the propeller blades in the fluid which has a hydrodynamic profile. In particular, Equation 8 is obtained from a dimensional analysis that allows to relate this force with a coefficient called KT.

$$FP = K_T \left(\frac{\omega_m}{2\pi}\right)^2 D^4 \quad (8)$$

KT coefficient was defined in Modeling Hypothesis and is related to the advanced number J, that is zero when ω_m=0. J is defined as

$$J = x_2(1-\omega_m)\frac{2\pi}{D\omega_m}, \omega_m > 0$$

Equation 9, that constitutes FAC, is considered the total resistance whose values for this case are obtained by computational tools, varying the linear velocity x_2 and draft c (Equation 10).

$$FAC(c, x_2) = p_{00} + p_{01}x_2 + p_{20}c^2 + p_{11}cx^2 + p_{02}x_2^2 + p_{21}c^2x_2 + p_{12}cx_2^2 + p_{30}c^3x_2 \quad (9)$$

$$c(z_1) = 0.087 - z_1 \quad (10)$$

Table 4 shows the values of the coefficients.

Table 4. Parameters of FAC.

Parameter	Value for $x_2 < 1.4875$	Value for $x_2 \geq 1.4875$
p_{00}	0	85.95
p_{10}	0	-2.06e3
p_{01}	24.56	-27.76
p_{20}	0	6.03e3
p_{11}	-667.79	723.3
p_{02}	4.13	4.6345
p_{30}	957.49	0
p_{21}	4.81e3	0
p_{12}	46.35	0

For FAT, the resistance corresponds to a theoretical drag force of the rudder (Equation 11) considered as a submerged element, whose cross section equals a hydrodynamic profile with a known drag coefficient.

$$FAT(x_2) = 1.1261\,x_2^2 + 1.2423\,x_2 \tag{11}$$

FB is governed by the Archimedes' principle and according to the third modeling hypothesis, the displacement is obtained as a function of the draft. This represents a quadratic regression for the submerged volume of the boat according to its draft. This expression is multiplied by the specific weight γ of water (Equation 12).

$$FB = \gamma(15.57c^2 + 0.78c) \tag{12}$$

W is the weight of the catamaran.

$$W = mg \tag{13}$$

The fixed structural support consists of a damper and a spring, which constitutive equation is defined based on Hooke's law (Equations 14 and 15).

$$FA = \beta z_2 \tag{14}$$

$$FK = kz_1 \tag{15}$$

Equations 16, 17, and 18 are the result of applying the Lenz law to obtain the induced voltages in each line.

$$e_a = \frac{k_{em}}{2}\omega_m F(\theta_e) \tag{16}$$

$$e_b = \frac{k_{em}}{2}\omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \tag{17}$$

$$e_c = \frac{k_{em}}{2}\omega_m F\left(\theta_e - \frac{4\pi}{3}\right) \tag{18}$$

The electrical torque τ_e is generated by the induced forces on the rotor and it is the result of the sum of the torques in each phase (Equation 19). This is explained by Biot-Savart law.

$$\tau_e = \frac{k_{tm}}{2}\left[F(\theta_e)\,i_a + F\left(\theta_e - \frac{2\pi}{3}\right)i_b + F\left(\theta_e - \frac{4\pi}{3}\right)i_c\right] \tag{19}$$

$F(\theta_e)$ is a trapezoidal, periodical, and piecewise function that depends on the electrical angle. Equation 20 represents each 2π period of $F(\theta_e)$.

$$F(\theta_e) = \begin{cases} 1, & 0 \le \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right), & \frac{2\pi}{3} \le \theta_e < \pi \\ -1, & \pi \le \theta_e < \frac{5\pi}{3} \\ 1 + \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right), & \frac{5\pi}{3} \le \theta_e < 2\pi \end{cases} \tag{20}$$

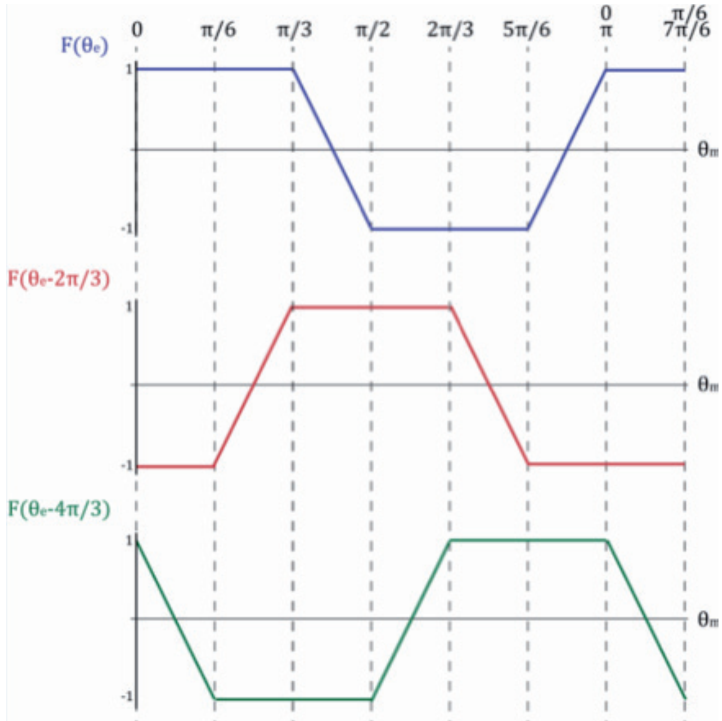
The electrical angle θ_e is related to the mechanical angle with the expression θ_e=p/2 θ_m where p is equal to the number of poles of the motor. In case of a four poles motor, as in this model, Equations 16-19 can be expressed in relation to the angle θ_m and describing the commutation that occurs in the inverter (Equations 21-23). Fig. 7 is a graphic representation of these functions.

$$F(\theta_e) = \begin{cases} 1, & 0 \le \theta_m < \frac{\pi}{3} \\ 5 - 12\frac{\theta_m}{\pi}, & \frac{\pi}{3} \le \theta_m < \frac{\pi}{2} \\ -1, & \frac{\pi}{2} \le \theta_m < \frac{5\pi}{6} \\ -11 + 12\frac{\theta_m}{\pi}, & \frac{5\pi}{6} \le \theta_m < \pi \end{cases} \tag{21}$$

$$F\left(\theta_e - \frac{2\pi}{3}\right) = \begin{cases} -1, & 0 \le \theta_m < \frac{\pi}{6} \\ -3 + 12\frac{\theta_m}{\pi}, & \frac{\pi}{6} \le \theta_m < \frac{\pi}{3} \\ 1, & \frac{\pi}{3} \le \theta_m < \frac{2\pi}{3} \\ 9 - 12\frac{\theta_m}{\pi}, & \frac{2\pi}{3} \le \theta_m < \frac{5\pi}{6} \\ -1, & \frac{5\pi}{6} \le \theta_m < \pi \end{cases} \tag{22}$$

$$F\left(\theta_e - \frac{4\pi}{3}\right) = \begin{cases} 1 - 12\frac{\theta_m}{\pi}, & 0 \le \theta_m < \frac{\pi}{6} \\ -1, & \frac{\pi}{6} \le \theta_m < \frac{\pi}{2} \\ -7 + 12\frac{\theta_m}{\pi}, & \frac{\pi}{2} \le \theta_m < \frac{2\pi}{3} \\ 1, & \frac{2\pi}{3} \le \theta_m < \pi \end{cases} \tag{23}$$

Fig. 7. Plot of F (θ_e) in terms of θ_m.



Moreover, the commutation in the inverter must be done in a way that satisfies the conditions for u_a, u_b and u_b depending on the angle θ_m (Table 5).

Table 5. Voltage value in each phase according to clockwise rotation.

Electrical angle θ_e	Mechanical angle θ_m	u_a	u_b	u_c
0-π/3	0-π/6	$u_{dc}/2$	$-u_{dc}/2$	Not connected
π/3-2π/3	π/6-π/3	$u_{dc}/2$	Not connected	$-u_{dc}/2$
2π/3-π	π/3-π/2	Not connected	$u_{dc}/2$	$-u_{dc}/2$
π-4π/3	π/2-2π/3	$-u_{dc}/2$	$u_{dc}/2$	Not connected
4π/3-5π/3	2π/3-5π/6	$-u_{dc}/2$	Not connected	$u_{dc}/2$
5π/3-2π	5π/6-π	Not connected	$-u_{dc}/2$	$u_{dc}/2$

τ_L corresponds to the load torque of the propeller (Equation 24). This one, is obtained from a dimensional analysis like FP term above mentioned. Likewise, the torque coefficient KQ was defined in Modelling Hypothesis.

$$\tau_L = K_q \rho \left(\frac{\omega_m}{2\pi}\right)^2 D^5 \qquad (24)$$

τ_D is the torque that corresponds to the viscous friction of the motor shaft and its direction is opposite to the sense of rotation of the shaft (Equation 25).

$$\tau_D = B_m \omega_m \qquad (25)$$

System's Model

The Equations (26)-(33) are the ones that make up the model and allows the system to be solved.

$$\frac{d\dot{x}_2}{dt} = \frac{FPcos\theta - FAC - FAT}{M} \qquad (26)$$

$$\frac{d\dot{z}_1}{dt} = z_2 \qquad (27)$$

$$\frac{d\dot{z}_2}{dt} = \frac{FPsin\theta - FK - W + FB - FA}{M} \qquad (28)$$

$$\frac{di_a}{dt} = u_a - Ri_a - e_a \quad (29)$$

$$\frac{di_b}{dt} = u_b - Ri_b - e_b \quad (30)$$

$$\frac{di_c}{dt} = u_c - Ri_c - e_c \quad (31)$$

$$\frac{d\omega_m}{dt} = \frac{\tau_e - \tau_l - B_m \omega_m}{J_m} \quad (32)$$

$$\frac{d\theta_m}{dt} = \omega_m \quad (33)$$

Simulation

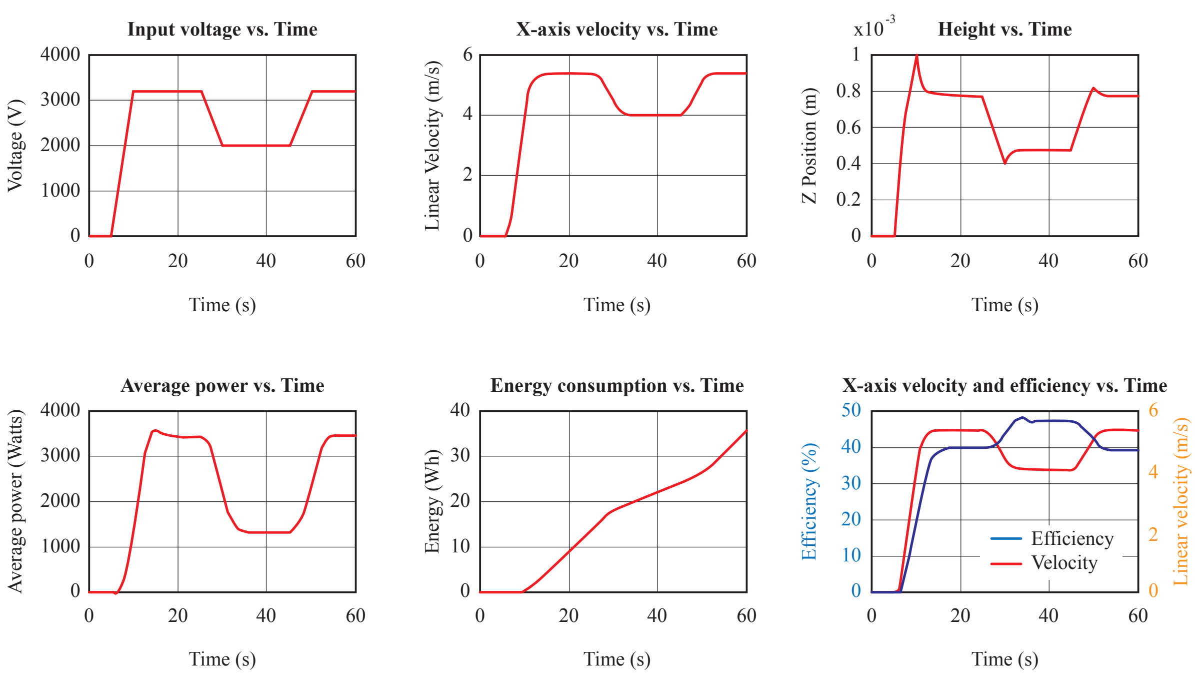
The previous equations, constants and parameters were programmed in MATLAB to solve the system of ordinary differential equations (Fig. 8). The input voltage is an input for the model, and it is chosen according to the desired speed profile, including positive and negative acceleration.

It can be observed that the vessel's translational speed has a growing behavior until it stabilizes, consequent to the input voltage that the motor receives. Besides, due to the restrictions imposed in the structural support and before the vertical position stabilizes, there are some peaks smaller than one millimeter in very short periods of time. It is evident as well that there is positive acceleration when the voltage increases, and the vessel tends to increase its position in the Z axis. Analogously occurs when the acceleration is negative.

With this information, the motor's average power is obtained over time. This information would be useful when the real values are required according to the voltage input and the speed variation. In this case, it would be necessary a 3500 watts power to get a 5.4 m/s velocity. After integrating the area under the power's curve, it is possible to find out the total energy consumption behind a speed routine. As a result, the motor-propeller efficiency (Equation 34) is invariant in steady state and reaches its maximum efficiency when it stabilizes at the smallest speed. That is related with the behavior of FAC: if the vessel's speed is increased, the required power grows exponentially.

It is shown that the developed model has accurate responses to the variation of the voltage of vessels with electrical propulsion. Now, it can be

Fig. 8. System simulation.



considered as a tool for the energy consumption evaluation, and if is required, the speed and motion range in which the catamaran is going to move.

$$E_{mp} = \frac{T_L \omega_n}{Pow_{elec}} \cdot EFFY \tag{34}$$

Where, Pow_{elec} is:

$$Pow_{elec} = (Ri_a + e_a)\, i_a + (Ri_b + e_b)\, i_b + (Ri_c + e_c)\, i_c$$

and *EFFY* is given by:

$$EFFY = \frac{K_T J}{2\pi K_Q}$$

Conclusion

During the design phases, the calculation of energy consumption has an important role in the economic and environmental aspects.

The greatest contribution of the model is to provide a tool that allows the verification of parameters evaluated in the vessel design in a more precise way in comparison to the traditional method. For example, the values of consumption are generally obtained in points of specific operation that do not describe in an explicit way, the craft behavior.

Considering the initial considerations and simplifications of the model, for an industrial application it is imperative to reduce the restrictions. Consequently, it is important to increase the degrees of freedom and obtain a model with high reliability for future work.

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Latam Shipbuilding Competitiveness

Competitividad de la industria naval latinoamericana

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Abstract

After an introduction on the region's shipbuilding industry, it moves into an analysis of some aspects of this industry's competitiveness, comparing Latin American (LatAm) shipyards with those of other regions with more developed industries. Among the m se aspects are: productivity, learning curve, specialization, labor cost, delivery times and government policies.

Second part deals with specific opportunities for domestic shipyards and ideas for developing their competitive advantages to generate value and social impact in the region, while safeguarding the environment. Six niches or opportunities are presented here, which are in all cases related to casting a new regard on Nature in our region. Nature being understood as the sum of natural resources, with the riches in fishery and offshore hydrocarbons standing out among them, but also those of the broad navigable rivers and lastly that of a privileged geographical position in terms of the extreme closeness to the Antarctic.

Key words: Shipyards, shipbuilding competitive factors, LATAM shipbuilding industry.

Resumen

Tras una introducción sobre la industria naval regional se avanza en analizar algunos aspectos de la competitividad de esta industria, haciendo comparaciones de astilleros latinoamericanos con los de otras regiones con industrias más desarrolladas.

Luego se presentan algunas oportunidades específicas de los astilleros latinoamericanos e ideas de cómo desarrollar las ventajas competitivas para generar valor e impacto social en la región, cuidando el ambiente. Estos seis nichos se relacionan con el uso de los recursos naturales entendidos en sentido amplio, incluyendo riqueza ictícola, hidrocarburos costa afuera, disponibilidad de grandes ríos navegables y cercanía a la Antártida.

Palabras claves: Astilleros, factores de competitividad industrial naval, industria naval latinoamericana

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In order to present specific opportunities of development, six niches are analyzed where competitive advantages are found for LatAm shipyards.

The work is manly focused on new ship construction and is part of major research effort that will be presented in a future publication *Shipbuilding in Latin America, 100 years (1970-2070).*

Latam Shipbuilding Competitiveness aspects

Boundary Conditions

As a basic simplification it's possible to differentiate two large groups (hemispheres) of countries of the region: those of the Pacific + Caribbean and those of the Atlantic.

The maritime industries of the Pacific hemisphere are characterized by being led by state-owned shipyards, connected to their Navies even if their output isn't exclusively military. Such are the cases of ASMAR in Chile, SIMA in Peru, ASTINAVE in Ecuador, COTECMAR in Colombia and DIANCA in Venezuela, among others. Another characteristic of this group is an overall trend of slow but continuous growth without major upheavals, and their relatively higher share of ship repair activities.

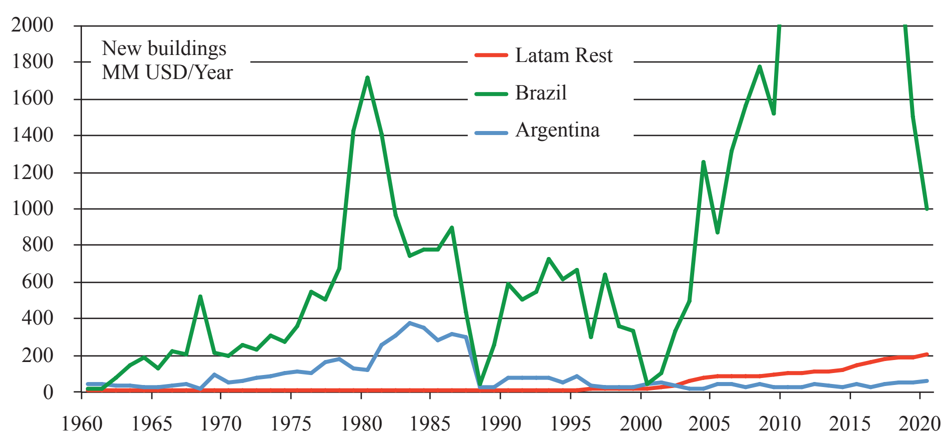
The Atlantic region, for its part, is practically the opposite. It is marked by the preponderance of private shipyards, by a higher relative participation in new constructions and by their characteristic cycles of bonanza followed by times of profound crisis mainly related to changing government industrial policies. This side of the continent exhibits the largest volumes of shipbuilding output, led by a vast margin by Brazil, the shipbuilding industry of which is by itself several times higher than that of the all the rest of Latin American countries put together. Ranking second in size is the case of Argentina despite the fact that it has already spent three decades of stagnation forced by the worst imaginable public policies. Also, to be mentioned are the cases of Paraguay with a growing development of "brown water" constructions and of Uruguay at a much more incipient stage.

In Fig. 1, a Timeline graph presents the Value evolution of the ship new building of Brazil, Argentina and the Rest of LatAm. This last one is based on gross estimates and it is steadily growing in this century mainly due to the output of Chile, Colombia and Paraguay.

International Industrial Competitiveness

It is a fact that shipbuilding is not isolated from the rest of the country economic environment and that ships are capital goods that are traded at the international market. For that reason, it

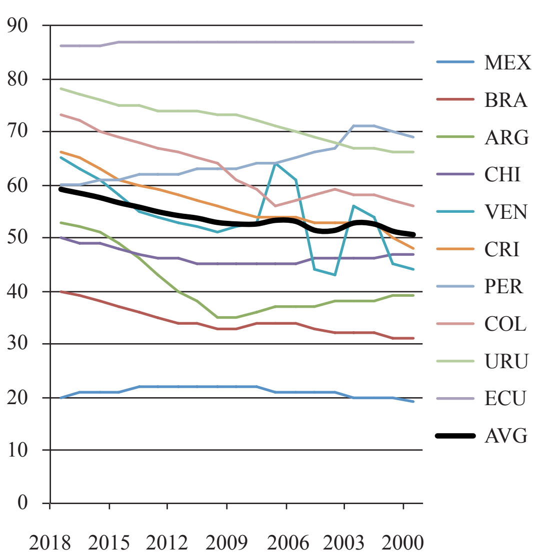
Fig. 1. Shipbuilding Development in Brazil, Argentina and Rest of LATAM.



is interesting to have a look at LatAm countries competitive ranking position in the global arena. This is presented by the *United Nations Industrial Development Organization (UNIDO)* who develops the Competitive Industrial Performance Index (CIP). The relevance of this index to the competitiveness of shipbuilding industries is demonstrated by realizing that over 90% of global ship production is concentrated in the top seven countries of the CIP 2010 [10] ranking (Japan, Germany, USA, Korea, Taiwan, Singapore and China). But in CIP 2018 this concentration increases even more (top 4 countries). In the region, the top four industrially competitive countries in 2010 were Mexico, Brazil, Argentina and Chile. Taken together, Brazil, Mexico and Argentina accounted for 4.2% of world manufacturing value added and 3.7% of world manufactures trade.

Among the 133 countries considered, the top ten LatAm performers are presented in Fig. 2, confirming a fairly stable ranking position during the first decade of the century, but they decline in the second decade. LatAm countries have lost positions, making more difficult to compete internationally with industrialized goods as ships.

Fig. 2. Top 10 LatAm International Industrial Competitiveness Ranking.



Shipbuilding Competitiveness

When analyzing the different aspects of competitiveness, it is possible to identify several “external” factors, beyond the control of a shipyard’s management. Meanwhile, “internal” factors, which can be controlled by industry executives, constitute its “intrinsic competitiveness.” As industrial economic entities, shipyards seek to grow competitively to better achieve the objectives of their shareholders, who can be private or governmental. This aspect leads us to one of the first issues to the analyzed and which is, precisely, the difference between state-owned and private shipyards, since both exist in LatAm.

Sate-owned shipyards and competitiveness

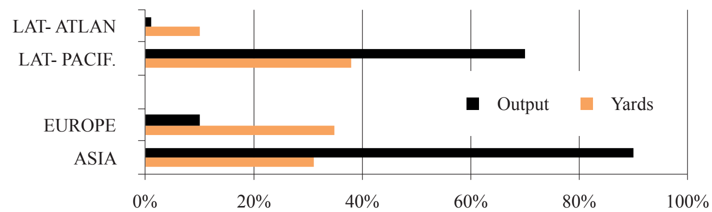
A recent study [6] which presents the relative importance of state-owned shipyards in different regions is combined with the LatAm case [7], showing, in Fig. 3, the market share of State-owned shipyards, their ratio of profit and employees to sales (in millions of dollars). As the argentine state-owned yards have a very poor average performance (in red numbers) they cannot even be shown in the graphs.

The above-mentioned study concludes that, in general, state-run shipyards are less efficient and flexible than private ones, making them intrinsically less competitive, and that the state-owned ones analyzed between 2012 and 2017 had an Employee/ Sales ratio of twice that of private shipyards, that being one of the most widely accepted parameters of lack of intrinsic competitiveness.

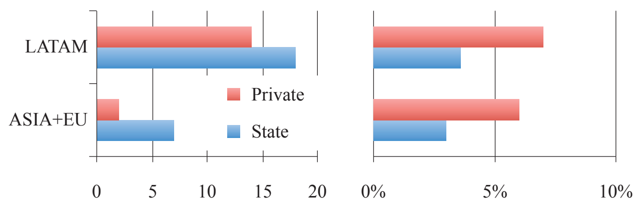
Lastly the OECD study mentions that the decisions taken by state-owned shipyards tend to be more closely related to political and electoral purposes than to criteria of industrial competitiveness, and refers to situations of disloyal competition between governmental shipyards and their private peers at national and international level. In the Argentine case there are several situations of this kind in its shipbuilding history, and in the Chilean case this constitutes one of the complaints of industry, according to a published survey [5].

Fig. 3. State Owned Shipyards performance in LatAm and the World.

	S.O.YDS / TOTAL	
	YARDS	OUTPUT
ASIA	31%	90%
EUROPE	35%	10%
LAT-PACIF.	38%	70%
LAT-ATLAN	10%	1%



		S.O. YARDS PERFORM	
		JOB/USD	PROF/SALES
ASIA & EUROPE	S.O.YDS	7	3%
	PRIVATE	2	6%
LATAM	S.O.YDS	18/150	3,6%/-500
	PRIVATE	14	7%



When comparing the performance of Argentine state yards with similar ones (ASMAR, COTECMAR, SIMA) throughout the region, it is found that in Argentina overstaffing is significant, productivity (Employment/MMUsd) is much worse, and structural losses have remained unresolved for decades, mainly in Rio Santiago shipyard.

Productivity

The most customary index for measuring this (for sizable ships) is the amount of Compensated Gross Tonnage (CGT) produced in relation of the unit of Man-Hours (MH) worked. The best levels attained in LatAm was at Brazilian yards, prior to the crisis of the 1990s, and were of the order of 65 MH/CGT and the average stood at 85, while Korean shipyards stood (1992) at 45 [9]. But for medium and small size ships that are the vast majority in LATAM case, the parameter of MH/CGT is not the most adequate, and given the different type of vessels built a better parameter would be Jobs/MMusd of production value.

Fig. 4 [7] shows the cases of more than 95% of world production on three continents. Brazil and Argentina (private shipyards) exhibit similar ratios, in the order of 21 jobs per million dollars of production, as do those of Latin America's principal Pacific shipyards, showing that, in comparison with other regions, there is still much room for improvement.

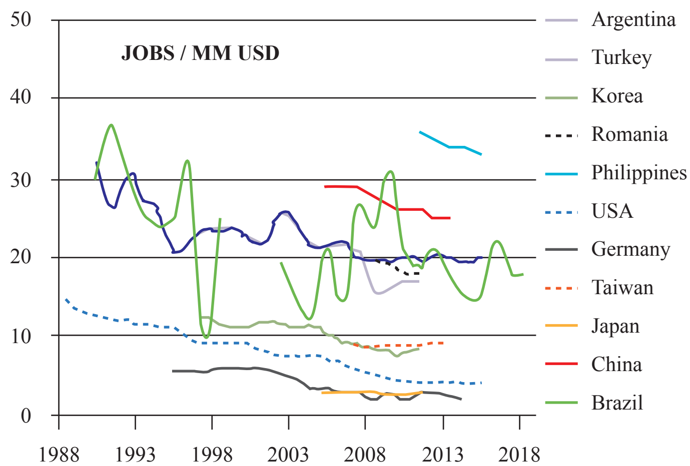
In Mexico [3] the average ratio for 2009 and 2014 was much higher, in the order of 47 Jobs/MMusd. One reason for the curves to tend downwards is the global trend to external subcontracting, keeping only the most essential tasks concentrated in shipyards, like assembly, project management, final outfitting, testing, launching and site management.

International studies [4] show much lower values for high production regions: Values for Japan and Europe are close to 6 jobs/MMUsd, South Korea, 4 and China, 10.

Learning curve and Continuity

Shipbuilding industry is characterized by a slow product innovation, so that advantages are achieved via continuous process improvements over the course of time, through learning. The concept of "continuity" needs to be stressed, for the positive effects of the learning to be really effective. In the cases of Korea and Japan, their current very high levels of productivity are mainly due to thirty years of continuous shipbuilding activity. In the case of LatAm, the larger shipbuilders (Brazil and Argentina) have never managed to maintain continuity for more than 15 years. This is not the case on the LatAm Pacific hemisphere where yards have enjoyed longer periods of continuous work but at a smaller scale.

Fig. 4. Shipyard Productivity (Employee/Value).



Improvement depends on the position of shipyards on their learning curve. Brazil stood (2012) with a factor of 85% [9]. This means that for every doubling of cumulative production, the improvement in productivity would be of 15% in terms of MH/CGT. For comparison purposes, the Asian countries that are most advanced on the curve stand at a factor of 70%.

Continuity is one of the most important factors to attain higher levels of competitiveness for the previous reasons and others as will be seen later on.

Repetitive production/specialization

Shipyards achieve higher competitiveness when they carry out repetitive construction.

Brazilian yards have begun to specialize but without sufficient repetitions. A case of success [2] was the Brazilian yard Wilson & Sons that expanded, investing in technology to specialize in the Offshore Support Vessels niche. In Argentina and Paraguay there are good examples in the barge building niche. But, again, the lack of continuity due to bad government policies stopped these developments, destroying the value generated.

Labor and Total cost

The labor cost at a Brazilian yard, working regularly in a continuous manner in the 1985-1996 period was of between 40% and 60% of the Japanese cost and between 50% and 70% of Korea's.

That same study explains that labor share in total cost strongly depends on the wage level and labor intensity of the process. In Europe and Japan may vary from 23% to 50%, in Korea are close to 19% and in India may be as low as 8% of total shipbuilding cost. As a general value [4], it is concluded that over half of the costs are equipment and materials (55% to 65%) and the rest is labor, services and overhead.

An analysis dated 1999 shows that total costs in Brazil for local yards were 40% higher than the best international ones, but were only 5% above international ones as regards their export, by reason of the lower applicable taxes and lower demands for the use of local marine parts which were more expensive.

Studies in 2013 show that the price of steel accounts for 20%/30% of the cost and that Brazil has been efficient as regards that output. Labor represents between 15% and 20% of the cost of ships, and equipment is 30% to 50% of cost.

Delivery times:

The average delivery time of Brazil's five largest shipyards between the years 1983 and 1996 was of 68 months, but that period was marked by several crises with production discontinuities. The case of Ishibras, between 1990 and 1994, is more realistic since it operated in a continuous manner on a series of eight Suezmax oil tankers for export with an average delivery time of 82 weeks, which can stand comparison with timeframes in Korea (27 weeks) and Europe (66 weeks). That was the Brazilian best performance.

Barge building in Argentina and Paraguay have reached very short delivery times in a series production system (as low as one 2500dwt barge per week at SANYM yard in year 2000) but still far from US yards output of on 1500 dwt barge per day.

Government Policies

Many countries consider the maritime industry as strategic, for which reason they generate protection mechanisms that guarantee its existence. A 2001 study by UNCTAD [1] identifies 17 types of maritime subsidies, and the countries that apply them. These policies are mainly in support of shipping lines and several are also, indirectly, an incentive to shipyards. Brazil is located in an intermediate position, applying 41% of the policies in 2001, in the following years increasing this both in number and in magnitude of application. At the same time, more than 60% of countries with a maritime industry apply the following policies: Coastal Traffic Reservation, Bilateral Agreements, Tax Reductions, Financing Programs and Subsidies.

Experience indicates that promoting the supplying of the domestic market is a good way of achieving sectorial development. But it is also markedly important to seek technological development, increases in productivity and the development of suppliers, since only those that are internationally competitive will thrive when, for some reason, the protections are reduced.

Korea and Japan are recent successful examples of industries that were strongly protected and promoted over a period of time and that gradually generated such competitiveness that it allowed them to continue to compete after the subsidies were reduced. In any event their governments follow developments attentively and act in their defense in crisis situations.

Nevertheless, competitiveness must not be sought at any price. Policies must, whenever possible, be created without cross subsidization such that other industries finance the shipyards or ship owners. Although subsidies are frequently necessary at moments in which an industry is recovering, they must be transitory and be gradually reduced.

In Colombia the programs AntiTrámite and ProAstillero are very positive actions towards eliminating productivity barriers, as well as the recent decree 1156/2020 that eliminates import duties on 350 items of parts required to build ships in Colombia.

Government actions on crisis

Shipbuilding is cyclical and continuity is key to competitiveness. Therefore, it is expected that governments will take action to protect the high valued competitiveness attained by their respective shipyards when a crisis arises.

In LatAm we have basically two very different attitudes: In Brazil and Argentina, governments have suspended all kinds of supports during low cycles, worsening the crisis and losing all the competitive edges developed. In the Pacific hemisphere, governments keep supporting (at least at a minimum level) the state-owned yards during critical times, thus permitting them to keep building productivity.

In the rest of the world, some of the actions to support the shipbuilding industries during 2007 crisis were [4] the following: Korea announced 18 billion Euros support package to shipyards and the ExImBank put aside 8,5 trillion won for loans to small yards and encourage private banks to facilitate guarantees for ship export operations. The "Build in India Policy" was launched with large funding and 30% subsidies for orders placed before August 2007 and 20% for those placed onwards. USA put a special stimulus package with a large budget to acquire a fleet of public service vessels, such as ferries. The "Build in Turkey Policy" offered extended facilities for ship exports and provided financial support for shipyards in trouble.

Six niches of LatAm Shipbuilding Competitiveness

It is unrealistic to expect LatAm shipyards to be competitive in all type of vessels. Therefore, it is wise to identify the most convenient niches and concentrate in them.

Fisheries

Both the South Atlantic, close to Uruguay and Argentina, and the South and Central Pacific alongside Chile, Peru, Ecuador, Colombia, Mexico and Central America, are among the richest fishing grounds at worldwide level, and coastal nations have an ample tradition of fishing activities and construction of fishing vessels. Nevertheless, the majority of larger-sized fishing vessels are imported, and local industries must settle for building smaller crafts, as if it weren't possible to build them competitively in each country, or at least at regional level.This is clearly the result of bad state public policies, across the continent, which in many cases answer to a combination of lack of information, indifference and corruption. Argentina's fisheries case is paradigmatic. Despite having a large maritime construction capacity, more than half of its fishing vessels have been imported secondhand and tax-free, representing 85% of current hold capacity [7]. The last fifteen Argentine governments expedited the free importation of secondhand fishing vessels larger than 40 m in length, arguing that they couldn't be built in Argentina, even as domestic shipyards were delivering larger and more complex ships for local and export markets.

The fishing nations par excellence (Spain, Japan, Korea and China) dump their played-out ships in these underdeveloped fisheries and thus modernize their own fleets; and additionally position their own firms to thus ensure control over these key natural resources.

Without going into the political debate on the best way to exploit each country's oceanic resources, what is indeed clear is that our governments should prioritize local ship construction. If shipyards weren't prepared for it, foreign firms could be incentivized to set themselves up and build the ships locally. And in those countries where the industrial capacity does exist, agreements could be generated for foreign companies to contribute all the imported equipment for building the vessels locally.

This natural wealth that belongs to all of us inhabitants of each fishing nation needs to be shared out better, among us, the owners of the resources. One way to do it is precisely by promoting the domestic construction of the ships involved. And in this process, we will in addition, be doing it with ever rising competitiveness – something that will never be achieved if we import what we are able to build.This is undoubtedly an opportunity niche for increasing in competitiveness.

Offshore Oil and Gas Production

As with the case of the fisheries resource, that of offshore oil and gas should be regarded as an opportunity for the development of the owners of this resource, who are neither governments nor oil companies, but the current and future inhabitants. And one of the fastest and most profound ways of achieving this is through construction of the support vessels, platforms and ships for this activity with rising levels of domestic content.

The case of offshore in Brazil is exemplary for understanding the transformative capacity of the marine industry, which took employment at the shipyards from 2,000 workers at the turn of the century, to some 80,000 a decade later. But for this to happen there was a state policy strongly maintained over time [8].

Brazil convinced the world's largest builders of offshore structures and vessels to associate with domestic companies and produce as much as possible in Brazil, contributing capital and technology. The results were amazing and the first signs of rising competitiveness began to arise especially in the construction of offshore support vessels, but the oil crisis and the cases of corruption at Petrobras blocked the effort – which, nevertheless, left its mark and much acquired knowledge, making it possible to aim at Brazilian exports for an offshore African development exhibiting similarities.

This is likewise an opportunity niche for the incipient offshore oil and gas production of Chile and Argentina and the more advanced ones in the rest of Latin America. Certainly, with a lower potential than Brazil, but, over the course of time, a rising presence of our shipyards in this sector will allow us to enjoy a clear competitive development.

Coastal and Oceanic Patrolling

As was mentioned above with regard to fishing activities, our Latin American seas contain great wealth. It's not in vain that pirate fishing fleets prowl around them in never-ending fashion.

Many Latin American countries began to take this path of domestic construction, increasing in experience and competitiveness. The best example is Chile's with its large series of locally built OPVs. But it is likewise the case of Peru, Ecuador, Colombia, Mexico and Brazil, which contribute 76% of regional content to the area's patrol fleets. Colombia stand out as their new OPV are Colombian designs. On the opposite extreme is Argentina that illegally imported a series of four OPV that could have been built locally.

This is a path that must not be given up and that should, rather, be strengthened, driving off the voices in alien languages that speak into the ears of our Navy officers and Defense officials attempting to convince them that their own people are unable to build OPV.

In actual fact the solution could be Solomonic. We should split it down the middle. We will import (in soft financing terms) from one concentrated international source the package of equipment that we still don't manufacture (which represents approximately 50%), with the condition that this (exporter) country also finances us the other 50% of the construction that we'll carry out in our countries. They will have a negative initial reaction, but they will quickly realize that other countries are starting to negotiate in these new terms and a new competition game will be starting, not for 100% of the vessels´ value but for the most profitable 50% (equipment, technology and systems).

River Transport

Another natural resource at our disposal is constituted by our rivers. The intensive use of Latin America's broad interior hydric basins is a key to achieving competitiveness regarding the output of the continent's interior, output which because of its low unit value requires systems of transport in bulk at very low cost. Such is the case of convoys formed by a series of shallow-draft barges and pusher. These convoys can be built, with high levels of competitiveness, at the shipyards of Argentina, Brazil, Colombia and Paraguay.

These are the type of vessels located on the lowest rungs of the scale of shipmaking complexity, and their real and virtually sole challenge is to produce them at low cost – which is in turn relatively easy to achieve when enjoying medium to long-term horizons, in order for the investments to be repaid and the effects of the learning curve to be maximized.

In this sense, one may turn to the case of the U.S. and its gigantic inland fleet, which enables transport on the Mississippi River to contribute maximum competitiveness to the output of the interior of that country under the protection of the centenarian Jones Act, which provides the maximum imaginable market protection.

Argentina and Paraguay had begun to attain very high productivity levels until the worst governmental decisions halted it, favoring the tax-free importation of secondhand vessels (junk) and killing off all the competitive achievements that had been reached.

Dredging and Port Services

Added to the above-mentioned flow of bulk products that arrive by river at the large export ports are many others that come by train or truck to be loaded onto gigantic bulk carriers with worldwide destinations. In the face of this situation, the immediate temptation is to hope to have those large ships, or a majority of them, built at domestic shipyards. Although at one time they were indeed built at Brazilian and Argentine shipyards, and some could undoubtedly be manufactured today, everything indicates that the chances of doing so competitively are virtually nil. This is because the large shipyards of the East outdistance us sidereally in this type of vessels and it wouldn't be a good allocation of scarce resources to attempt to compete in that market. It is better to set aside the resources for the niches with a greater probability of success.

Nevertheless, if we take a detailed look at the operation of those large bulk carriers, we shall find other opportunities. Such are the cases of the tugs that assist them in port maneuvers, or the buoy setters that mark off the access channels to the ports, or, lastly, the powerful dredgers that deepen, widen and maintain the channels for those bulk carriers to be able to leave with the maximum possible load and thus cause the incidence of freight to be lower and our products to gain in competitiveness.

Polar Logistics

There is no doubt that Chile and Argentina's geographical position, closer than any other country in the world to the Antarctic continent, puts them in a privileged competitive situation for providing Antarctic logistics services related to the maritime industry, such as maritime maintenance and repairs first and construction secondly.

In order to increase the competitive advantage as regards repairs it's necessary to have workshops and maritime repair shipyards at the southernmost ports such as those of Ushuaia and Punta Arenas. It must be understood that these services follow an export orientation, since the potential demand originates mainly from international fleets. These capabilities would also service the merchant vessels, fishing activities, the offshore activity off Tierra del Fuego and in the Strait of Magellan, and the increasing flow of cruisers.

As regards the ship construction of polar vessels both countries have had attractive experiences. In the case of Argentina, in addition to the construction of a polar ship in the 1980s, it has just concluded one of the world's most advanced polar projects with the modernization of the ARA Almirante Irízar icebreaker and there is a criticized project for the construction of a new polar vessel. In the case of Chile, marked progress is to be noted in the project of building a new icebreaker, which would be the first to be built in the southern hemisphere. At the same time, the Brazilian Navy has been holding talks with that of Chile for their participation in the construction of a new icebreaker for Brazil.

Other Activities

Only six market niches have been mentioned but there undoubtedly many other opportunities for competitive growth which it would be necessary to analyze. Among them could be that of coastal maritime transport; that of some vessels for defense; those of tourism activities, research work, short-distance passenger transport, and pilotage services. A very special attention shall be paid in LATAM shipyards to the huge market opportunities that is unfolding due to the impact in shipbuilding and ship conversions due to Climate Change urgencies.

Conclusions

It is concluded that competitiveness, for the type of vessels which the Latin American shipbuilding industry can realistically aim for (niches), must be analyzed not only at the level of the region or country but also at that of the shipyards. Increasingly, equipment, materials and technology are becoming commodities available to all at virtually the same international price. What makes a difference is the intrinsic productivity achieved within the country, and mostly, at shipyard level including its subcontractors. Nevertheless, whatever the efforts carried out at industrial management level, without an adequate governmental policy that generates a competitive environment and ensures horizons of continuity, generating temporary protections appropriate for facilitating development, it will be difficult to attain the levels of competitiveness that are needed in order to supply domestic markets, and especially to go out into the world exports market, which is what must really be aimed at to grow in volume and test competitive muscle.

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How to improve the shipbuilding industry with the Internet of ships concept

Como mejorar la construcción naval con el concepto de Internet of Ships

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Abstract

The goal of this research is to explain one of the most interesting technologies that exist today, Internet of Ships (IoS), the IoT applied to the maritime sector. This technology is an enabling of other existing within what is known as Industry 4.0, such as the digital twin, cloud calculations or augmented reality.

Something as common as barcodes, were precursors of this technology and have been the cause of many stores have made the leap to smart tags, like RFID ones, which help them to perform both inventory and collection of things in the cashier, making that one jacket in the store an individual item in the collection of objects but perfectly controlled by the system. During the last years we have worked on implementing this transversal technology in the naval industry, and in this paper some examples will be shown.

Key words: Ship design, industry 4.0, IoS, digital twin.

Resumen

El objetivo de este artículo es explicar a los lectores una de las tecnologías más interesantes que existen hoy en día, Internet of Ships (IoS), el IoT aplicado al sector naval. Esta tecnología es habilitadora de otras existentes dentro de lo que se conoce como Industria 4.0, como por ejemplo el gemelo digital, los cálculos en la nube o la realidad aumentada.

Algo tan común como los códigos de barras, fueron precursores de esta tecnología y han sido los causantes de que muchas tiendas hayan dado el salto a etiquetas inteligentes, tipo RFID, que les ayudan a realizar tanto inventario como cobro en las cajas, haciendo que una chaqueta de la de al lado sean objetos completamente diferentes pero controlados por el sistema. Durante los últimos años se ha trabajado en implementar esta tecnología transversal en la industria naval, y en este artículo se van a mostrar algunos ejemplos.

Palabras claves: Diseño naval, industria 4.0, IoS, gemelo digital.

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Introduction to the future of CAD systems applied to shipbuilding

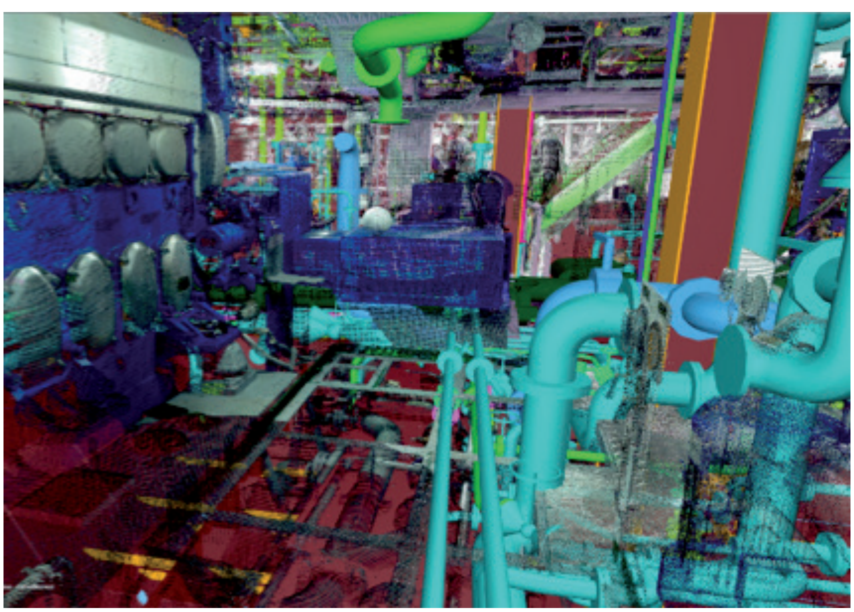
The objective of this article is to show how one of the technologies belonging to Industry 4.0, the Internet of Ships (IoS), can improve shipbuilding in the coming years. For such purpose, the implementation of this technology in ship design tools, also known by the acronym CAD (Computer Aided Design), has been studied over the last few years. Therefore, over the next few pages we want to explain how these design tools, used in shipyards all over the world, could improve in the near future.

As an introduction, we would like to analyze the current status of the functionalities that are currently being improved in CAD systems. E.g. in hull shape fairing or global shape modeling, complex surfaces could be transformed with excellent results, less interaction, high precision and full control. These techniques drastically shorten the design time, from days to minutes, obtaining excellent results *(Pérez & Alonso, 2015)*.

Another area of improvement concerns one of the most labor-intensive tasks in equipment design, the routing of piping, HVAC (Heat Ventilation Air Conditioning) ducts and cable trays. Automatic routing options minimize this time, but without reducing the robustness of the design. There are automatic routing algorithms, which provide simple solutions with material optimization. But the point is not just to consider existing elements for future routes; it is also necessary to assign priorities and eventually make automatic modifications to existing elements as a result of the incorporation of new ones. The complexity of the problem explains why a completely satisfactory solution for automatic routing does not yet exist. Current solutions provided by CAD systems solve partial problems, already offering significant support.

Another area where CAD development companies are very active is in Virtual Reality. The objective is to create a friendly environment for the user in order to review, audit, obtain metrics such as the progress of a project, etc. This type of model review process does not require the use of design tools, just a simplified tool that allows easy access (viewer). In Fig. 1, a 3D visualization model is reviewed on a mobile device, where authorized designers/engineers could have all the project information. These browsers allow access to the reading of 3D information to load the component tree of the projects and obtain information about any part. Other basic tools available in these programs have different modes and commands, making it possible

Fig. 1. The future of naval design and the emergence of Industry 4.0 in the naval sector.



to measure distances or angles, create sections to access internal components, etc. The interface with the program is through a mouse, but Virtual Reality offers more possibilities, such as goggles or headsets.

Advanced browsers make it possible to incorporate human models to study ergonomic aspects, create highlights and textures for advanced renderings, component movements for simulations, etc. Browsers can connect to a project's database to access information in real time. Sometimes it is necessary to take information from an online database and if there is an Ethernet network through the shipyard, it is possible to implement a shared computer with a viewer to connect to a project. If there is no accessible database, users should be able to read files with the project information required for 3D product modeling and component data with optimal performance. Until now, it was common to implement viewers on laptops, because laptops are usually equipped with processors and graphics cards that allow navigating through the entire project. In recent years there has been a great advance in mobile devices such as tablets and smartphones. This hardware progressively incorporates new processors that enable improved graphics. On the software side, operating systems have been developed specially adapted for such devices (such as Android or IOS) that allow for interaction naturally through touch gestures.

The widespread use of these devices today has precipitated their use by software companies. Software developers have taken their time preparing targeted solutions, including those that allow us to have project plans or 3D models on smartphones or other electronic devices. In modern projects, there is a need for technicians to carry these devices to make them work better, with quick access to the 3D model of the project, with all the necessary part information and construction drawings. A wi-fi connection would make it possible to connect to a server to update information, mainly in files, such as: 3D models, classification or production drawings, among others. Another advantage of mobile devices is that the user interface can interact with the model or parts of the project using gestures, just as with smartphones. A browser evolution development line would incorporate augmented reality technology. It would be useful for production technicians to scroll through the project and point the camera of their mobile device at a particular component to get information from it and display the actual image of the same 3D design model. This is possible through the use of markers that allow the device to position itself within the project and also through the use of QR (Quick Response) codes.

CAD systems must handle the necessary information to create a collision-free design and to generate all production and assembly information, but not only this. The 3D model information is, at the same time, necessary for other activities and other departments involved in the construction of the vessel, such as planning, purchasing, outsourcing, accounting, etc. It is common for several designers to collaborate on the same project; therefore, it is necessary that the 3D model information be shared among them for reference. The paradigm of this problem appears when two or more designers collaborate on the same project, using different CAD tools. In this case, CAD systems must provide data exchange between them, leading to different degrees of integration, such as visualization, spatial integration and cross-manufacturing, depending on the characteristics and size of the information transferred from the 3D model. At the very least, it should be geometry and key attributes. A worldwide format for data transfer has not yet been found. Despite recognized international standards, in most cases we see dedicated formats or particular adaptations of standard formats. The transfer of 3D model information could result in a loss of performance due to the different geometric approaches to represent elements that exist in both CAD systems. In this case, special solutions must be adopted to minimize this impact.

Another milestone is the integration between different CAD systems and Product Lifecycle Management (PLM) tools, *e.g.*, the architecture-neutral FORAN Product Lifecycle Management (FPLM) tool. In this case, all information generated in FORAN can be transferred to a PLM and can be subject to all processes: control, configuration and release lifecycle and process management. FPLM consists of a number of tools and functions that allow bi-directional integration between different FORAN and PLM tool modules. The solution is based on standards such as XML, Web Services and Common Object Request Broker Architecture (CORBA). Fig. 2 shows an example of tool integration. Colors highlight parts or elements that will or will not be transferred to PLM.

There are many advantages of using CAD systems in shipbuilding: ease of design, speed of construction, use and reuse of information, etc. In the future, CAD tools are expected to advance further and enable greater information management and virtual access through smart devices. In general, CAD systems provide tangible benefits while optimizing the process, reducing design and production time and therefore costs.

What is IoT and how does it apply to the software world?

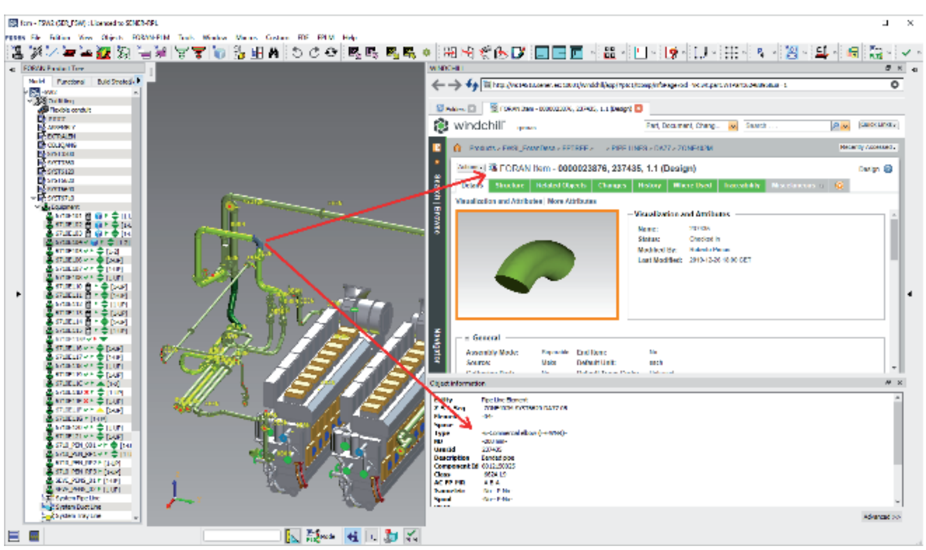
IoT is short for Internet of Things, which is known as the technology and process of connecting objects to the Internet. The goal is to make objects exchange data with the Internet and with each other *(Muñoz & Pérez, 2017)*.

The IoT concept was born at MIT's Au-to ID research center in 1999 after extensive research into the radio frequency identification of objects (known as RFID), which is Kevin Ashton's main idea. The idea of the research was to identify all objects and all people in some way, allowing some of the objects to exchange data with others via the Internet. Object identification was the prerequisite for IoT.

Humans interact with objects in a more or less direct way. But if objects are allowed to interact with each other, objects themselves may exchange data for their own needs. This would create a network of smart objects that can interact independently in the context of their mission. This network is known as IoT. The intelligence property of objects or devices need not be complex and exhaustive. For example, a refrigerator would require a way of measuring the elements so as to obtain information and recharge it when its charge is below threshold. These examples clearly show what device intelligence is.

In order to achieve connectivity, certain requirements must be met, including unique identification. But most importantly, it is necessary to determine whether the object is connected to the global network. The object will be related to its mission, but it will also be related to its needs so that it can fulfill its mission.

Fig. 2. Select an item in CAD scene and directly show simultaneously the item data in CAD and PLM.



Object connectivity requires various technical properties: hardware, connection method, and software. Hardware are physical devices that are intelligent, software are intelligent programs for the object, and the connection method is the way in which objects can communicate through physical or virtual devices (*e.g.*, radio frequency, wireless, etc.). Obviously, this is a very simple description of connection, but it is enough to illustrate the components involved in this concept.

The following four aspects can identify whether a product is connected to the IoT:

- Be able to control the use and operation of the product or object.
- Be able to be remotely operated or appropriately designed for use.
- Be able to predictively diagnose, repair or improve its performance.
- Any combination of the above.

There is enormous growth potential in this area and it can induce extraordinary potential economic growth. The McKinsey Global Institute report entitled "Disruptive Technologies: Breakthroughs that will transform life, business and the global economy" *(McKinsey, 2013)* concludes that the economic impact of IoT in 2015 has a potential annual growth of $2.7 to $6.2 billion. It further predicts that 80%-100% of the manufacturing market will use IoT applications with an economic impact of $0.9-2.3 billion *(McKinsey, 2015)*.

All economic sectors will be affected by this revolution. It will undoubtedly be the world of software and it will also be the case for shipbuilding. The vessel itself and all its elements will be linked to the connection, which can be done with this technology, opening up an extraordinary field.

The meaning of objects in IoT should not be limited to just physical objects. The concept can be extended to those programs called "virtual objects" that do not have a physical element. Therefore, we can know what the programs for IoT should be. And in particular, how should programs in the IoT world be oriented?

The origin of IoT can be found in the programs themselves. When a program suddenly stops working and indicates that there is a problem and if we want to transmit the diagnostic information to the supplier. This is an emerging IoT, although in this case it requires user acceptance. At other levels this acceptance is configurable and will be automatic.

These concepts can be applied not only to objects and devices, but also to CAD programs.

The Internet of Ships

According to the latest Juniper Research report, the number of connected devices in 2021 will reach 46 billion *(Muñoz & Pérez, 2017)*. As a comparison, this is a 200% increase vs. 2016. Many more will come, very quickly, and it looks like 2021 will be the year when 5G will definitively take off. This revolution, which started a few years ago, has aroused enormous interest in all industries and in some of them it is already operating with apparent normality.

The deployment of 5G networks will have a great effect on high-end IoT applications linked to robotics and automation, virtual and augmented reality, and artificial intelligence. Today it is difficult to buy appliances and household items that do not have an Internet connection.

From the Internet of Things Solutions World Congress in Barcelona, major Internet of Things trends include attempts at format simplification, Artificial Intelligence, Edge Computing and Digital Twin.

In this context, the question is how the shipping industry is adapting to this revolution. Is it possible that this traditional and conservative sector will move towards this technology?

Sea transport is facing a new scenario; Covid-19, even with IMO (International Maritime Organization) recommendations, has affected the sector. The changes in the creation of global value chains make the concept of IoT gain importance, and the result of this scenario will be the significant advancement of the digital era in this sector.

The new social distancing and prevention measures in the face of Covid-19 make it essential to use all the technology that we have adopted in recent years: cloud computing, collaboration tools (such as videoconferencing software, project management, chats), remote computer access and device synchronization, VPN and mobile-first applications.

There is already evidence that the shipbuilding industry is no stranger to these developments and is already connecting some ship components to the Internet, as shown in Fig. 3.

Just as there is a smart home or smart phone, there are new smart boats that are equipped with a network of sensors that capture a variety of voyage information, including:

- Location.
- Weather.
- Ocean current.
- Status of onboard equipment.
- Cargo status.

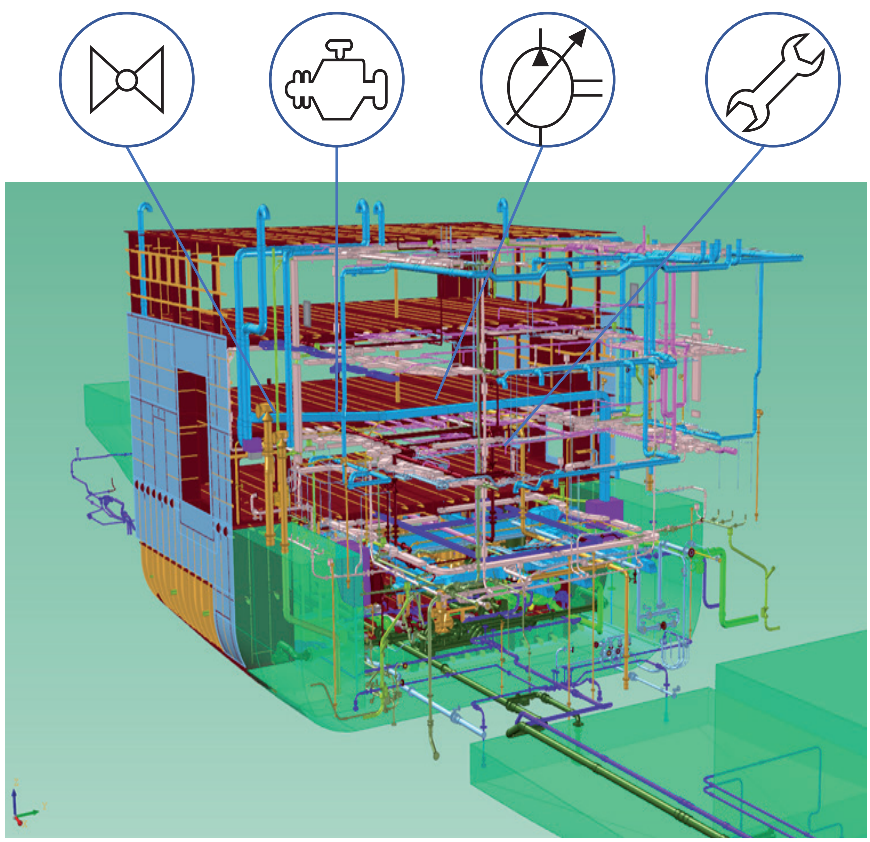
Ship owners can monitor the ship's status in real time and perform analysis on historical and current data to make decisions to operate more efficiently, saving time and fuel.

Sensors and technologies facilitate the introduction of new applications at sea, such as energy distribution, water control and treatment, real-time monitoring of equipment...

Sensors that, for example, collect air quality information and are connected to an Artificial Intelligence system that can turn HVAC systems on and off as needed.

The aim is to take advantage of this technological revolution by also acting in the design and production phases in order to build efficient, safe and sustainable vessels.

Fig. 3. Representation of a 3D model with access to the different components of the ship connected to IoT.



In a decentralized industry such as the naval industry, where engineering and production are often in different locations and where critical decisions cannot wait, the Internet of Ships (IoS), or the connection of critical components in ship design/construction, is beginning to loom as something the industry cannot afford to ignore. The idea is to monitor all those parts where early detection of situations allows us to make the right decisions.

In this sense, having sensors during the early stages of ship construction allows us to identify whether the ship's construction is completely in accordance with the design we have created with CAD. Whether we can reduce materials or use another one, if we have to adjust something according to naval architecture calculations...

Continuous monitoring with a ship design CAD, such as FORAN, will allow for cost reduction, error avoidance and real-time decision making from the shipyard, design offices or remote locations.

Today, CAD solutions such as FORAN can be used in pocket-sized tools, becoming an indispensable ally in this new technological revolution (see Fig. 4).

However, data management is only one side of the IoS coin. Energy efficiency is also a fundamental aspect in new devices that connect to the network. But IoS does not only cover the design or production stages of the ship, once the sensors are on the components which information we want to monitor, we can obtain information throughout the life of the ship.

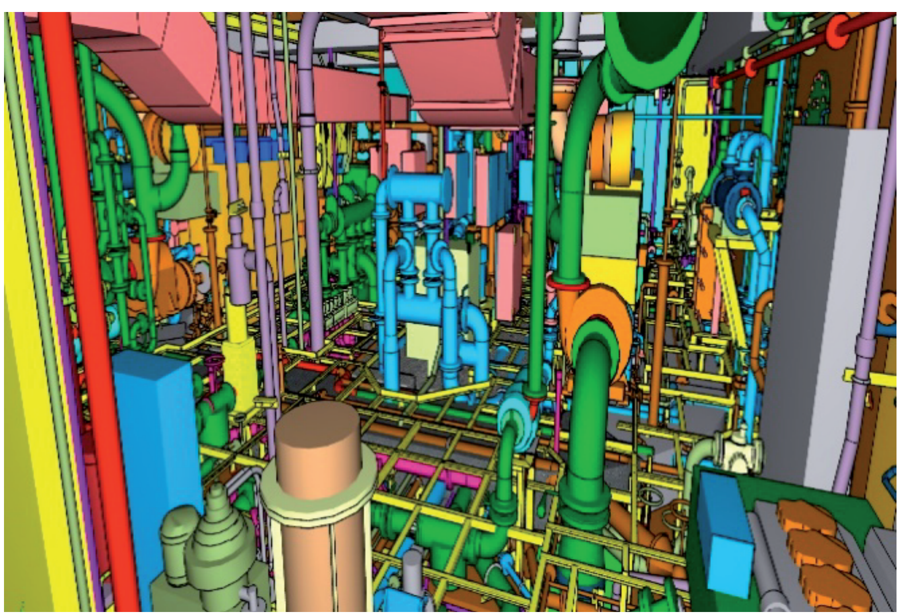
IoS is presented as a solution capable of detecting when a component of a vessel is close to failure and must be replaced, when we must take the vessel to be repaired, when we have to repaint, when corrosion has reached a certain limit... and all using our pocket-sized tool and with enough time in advance to avoid late or unexpected actions.

IoS comes to this sector to ensure a profitable production, a safe, efficient and sustainable process for all types of vessels, fishing vessels, tugboats, tankers, cargo ships, ferries, dredgers, research vessels...

The IoS in a shipbuilding CAD environment

How could this revolution affect the world of shipbuilding? Could we consider the IoS concept? Ship projects are developed with CAD platforms, but every day we seek comprehensive product

Fig. 4. 3D model in a virtual handheld solution such as tablets or smartphones.



development that involves the entire Life Cycle of vessels. We seek to integrate the CAD system with the PLM and to be able to conceive from the PLM the whole design and at the same time control the production and include the use of the vessel.

The PLM can contain information on all the ship's systems and also on all its components. If the components are designed for IoS, they will have a technology that will enable sharing their status, diagnostics, functionality with the PLM system that distributes the initial design.

The PLM can use this information to know if they are working properly or if we can improve their performance. It is also possible to identify whether the equipment needs to be maintained or needs to be replaced because its life is ending or because it is malfunctioning. It will be possible to determine and evaluate its performance by comparing it with other similar components or by comparing it in different operating periods. It will also be possible to know how its performance affects the operation of the entire product, *e.g.*, the vessel. In addition, if the connection of objects is made with their PLM, it would be possible to record their history, track changes, and know what their function or performance is after scheduled maintenance is performed.

In the case of a vessel, this connectivity will extend to its commercial activity, to act autonomously in the operating conditions. A commercial vessel can transmit its sailing status, cargo status, merchandise to be unloaded or reloaded.

All this means an enormous amount of information to manage and analyze. New programs must be developed to achieve the greatest use of that information, so that, in this way, the design of the ship can be improved from real design information and can be maintained by itself, there being a connection with this enormous existing information in the cloud and thus create a method in which objects can achieve a certain intelligence. The growth of IoS is linked to the increase of information and Big Data management, with the exception that IoS somehow identifies information, direction and order for a specific purpose, while the concept of Big Data is more generic.

The possibilities are countless, but the principle is the same. It should start at the initial design. It is necessary to consider what is needed to properly fulfill the mission of the atomic elements. These requirements must be configurable in the initial design from where they will be extended to the relationships between each of them with other entities. CAD is one of the first steps, because that's where the concept of each component begins to be systematically collected. Therefore, it is necessary to use CAD tools for IoS design.

IoS and CAD systems

Engineers design ships according to the requirements of the ship owner and Classification Societies, but some materials change due to new regulations applied during the time of ship design, lack of availability of materials or obsolete materials.

In all these cases, the Storage Control System (SCS) software should help design teams easily identify unsuitable materials in 3D modeling, reducing the cost derived from this problem by highlighting them.

For the pre-selection of materials in the equipment, smart tools connected to the SCS software can count the required materials based on the smart piping and instrumentation diagrams (P&IDs) that use the required materials in this 2D design.

These diagrams can have two design phases, basic and detailed, the first is applied in the first steps of the project and represents the main requirements and accessories of the equipment, but the second, applied in 2D or directly in 3D generates more accurate information. Electrical and electronic systems are based on the same principles, and CAD should help designers avoid design problems and interference.

In the case of the main structure, this design is made directly in 3D, in CAD software, avoiding delays in the steel work of the blocks and sub-blocks into which the entire ship is divided.

In this case, the selection is made based on the shipyard's standard scrap percentage and the required material, based on the quality, thickness and surface required.

The SCS software should have a bi-directional connection with the CAD system to feed the catalog components, reducing the waiting time for designers to use it, and when the systems/structure are mature enough, feeding the SCS software with all the materials used/required to issue the pertinent orders.

Finally, information maturity is a decision by the team design leader that requires human interaction and, based on CAD tools such as design rules and self-checking, can be done easily and quickly.

Materials should be collected, from CAD by maturity level, added to the ERP/PLM to control the workflow in the workshops and counted in the SCS software to help people in the purchasing department issue orders.

This is based on full interoperability between systems, all of them working as a single system.

The material in workshops can also be labeled, coded and stored for further production steps, which allows the CAD system to lock down items making them non-editable, and the PLM/ERP advances in the workflow, to trigger the next production step and the SCS software to add a new material into the production system.

IoS as IoT organs of vessels

By dividing each system into autonomous, self-regulating and interrelated IoT cells or Ship System (SB) IoT cells, overall system failures are reduced and problems in other parts of the ship that are not directly related to the system are avoided. Cooling systems can be divided into SB cells as follows, for example:

- Seawater suction.
- Main pumping group.
- Secondary/auxiliary/emergency pumping group.
- Main engine circuit.
- Discharge of seawater.
- General System Control (CGS).

Each SB generates inputs for other parts of the system, and at a global level, it can group all parts of the system in the engine control room, where the CGS easily displays the status of each cell and, also, some data can be distributed to the main control bridge console.

In this way, each CGS represents an organ of the vessel, as a summary of all the cells of the system represented by their shared information.

Each organ has a relationship with the others through the CGS. Continuing with our example, the total failure of the cooling system can communicate with the fuel and lubricant system, stopping the main engine to avoid a major problem. As well as with the main bridge to give an alarm, send a report to the ship owner and communicate via GPS (Global Positioning System) with the nearest port.

Based on all this information, the engine room engineers can start the repair process or wait if the problem cannot be solved with the tools and materials on board.

Extending the biological concept of system to the vessel, any system directly or indirectly related to propulsion can be an IoS System that groups all these organs to produce a single action on the vessel.

The creation of larger groups makes it possible to classify errors, problems and also improves maintenance, as each simplification requires a shorter list of spare parts.

The last organ is represented by the ship's brain, this is the main CGS that retrieves information from all IoSs, its organs and SB.

Conclusions

The recent emergence of Internet of Things (IoT) technologies in different industries has led shipyards around the world to be interested in applying the same technology to the naval industry, and this application has been called the Internet of Ships (IoS). IoS is the application domain of IoT in the naval industry, and refers to the network of smart and interconnected objects, which can be any physical device or infrastructure associated with a shipyard, a vessel, a port or sea transport itself, with the aim of significantly driving the naval industry towards an improvement in terms of safety, efficiency and environmental sustainability. This article provides a comprehensive review of the IoS paradigm, its key elements and main features. In addition, the state of the art has been reviewed for emerging applications, including improvements in CAD ship design tools. Finally, the open challenges presented and future opportunities for naval research, safety, ship data collection, management and analysis provide a roadmap towards the full application of IoS in the naval sector.

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Shallow Water Resistance Estimation for a Riverine Light Patrol Boat using Computational Fluid Dynamics

Estimación de la Resistencia al avance en aguas poco profundas para un Bote de Combate Fluvial de bajo calado mediante Dinámica Computacional de Fluidos

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Abstract

For the design of naval ships, the operational environmental conditions in which ship navigation will take place must be taken into account. The present study presents the effect of shallow water on ship's drag. Numerical simulations using Computational Fluid Dynamics with the Star CCM+ Commercial Software has been performed for sea depths in which the BCFBC Shallow Draft River Combat Boat will perform operations. A full-scale validation campaign of the simulations with the built boat has been developed. The shallow water effect on ship total resistance and the residual resistance for different depths and speed has been evaluated.

Key words: Computational Fluid Dynamics CFD, Ship Resistance, Shallow Waters, Experimental Fluid Dynamics.

Resumen

En el proceso de diseño de las embarcaciones militares se deben tener en cuenta las condiciones del ambiente operacional en el cual se desarrollarán las operaciones. En este artículo científico se estudió la afectación de la resistencia al avance debido a las aguas poco profundas. Realizando simulaciones numéricas mediante Dinámica Computacional de Fluidos con el Software Comercial Star CCM+ en las profundidades en las cuales realizará las operaciones un Bote de Combate Fluvial de Bajo Calado BCFBC. Se desarrolló una campaña de validación a escala real de las simulaciones con el bote construido. La afectación de la resistencia al avance total y la resis- tencia residual para distintas profundidades y velocidades fue analizada.

Palabras claves: Dinámica Computacional de Fluidos CFD, Resistencia al Avance, Aguas poco profundas, Dınámica de Fluidos Experimental.

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Introduction

The Science and Technology Corporation for the Naval, Maritime and River Industry COTECMAR has been characterized by promoting, leading and promoting the interests and maritime power of the country. Colombia is a country with a large maritime and fluvial extension, with more than 928,000 km^2 of maritime area and a fluvial extension of 24,725 km of rivers, 75% of which are navigable. The Colombian Navy is in charge of the surveillance and control of this large fluvial extension, which through the Marine Infantry is present in these areas. Colombian rivers are characterized by different soil conditions, water characteristics and depths that change in winter and summer. Considering the above, there is a need for river resources that allow for continuous navigation and military operations, even when river levels are very low in the summer.

To meet this operational need of the Colombian Navy, COTECMAR designed and built a Low Draft Fluvial Combat Boat (BCFBC), which meets the operational needs required by the Marine Infantry, thus allowing navigation and the development of military operations in shallow secondary and tertiary rivers during the winter and summer, generating a new capability for the Colombian Navy.

The design of such a boat entails the challenge of analyzing and determining the shallow-water drag effect for planing hulls. Hydrodynamic phenomenon that has been the subject of some numerical and experimental studies [1]. These studies are of great importance to determine the installed capacity required to meet the design requirements associated with this high operational demand.

In this study, full-scale numerical simulations of the BCFBC were made at different depths by

Fig. 1. Colombian Armed Jurisdiction [5].

Computational Fluid Dynamics CFD, using the commercial software Star CCM+, which is a multiphysics simulation tool for simulation of designs in real conditions, using finite volumes. In addition, a validation campaign was developed with experimental tests on the vessel once built at different depths to verify its performance. The characteristics of the boat are listed in Table I.

Table 1. Parameters of FAC.

	Value
Length at waterline, Lwl	7.05 (m)
Beam	2.42 (m)
Displacement	3.72 (ton)
Draft	0.33 (m)
Longitudinal Center of Gravity (LCG)	2.89 (m)

Numerical and Mathematical Model

Complex flows governed by turbulent effects with high Reynolds numbers and unsteady flows with large fluctuations in space and time such as those of Naval Hydrodynamics are governed by the Navier Stokes equations. Different methods have been proposed to capture these phenomena, which are characterized by the formation of turbulence at different scales, which generate a transfer of energy from large to small. These phenomena can be calculated by Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and using the Reynolds-Averaged Navier Stokes Equations (RANS) in which turbulence is modeled at all scales. Currently, in Naval Hydrodynamics the most commonly used method is RANS, providing a sufficiently accurate solution and with a reasonable computational and meshing capacity compared to DNS and LES.

Governing equations

Starting from the mass continuity equation and under the assumption that only incompressible flow is considered, Equation 1 can be written removing the influence of density as Equation 2.

$$\frac{1}{\rho}\frac{\partial \rho}{\partial t} + \frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (2)$$

Therefore, the Navier Stokes equations can be written as follows:

$$\rho\frac{\partial U_i}{\partial t} + \rho\frac{\partial (U_j U_i)}{\partial w_j} = \rho R_i + \frac{\partial \sigma_{ij}}{\partial x_j} \quad (3)$$

Where σ_{ij} is the total tension of a Newtonian Fluid.

$$\sigma_{ij} = -P\,\delta_{ij} + 2\,\mu\left(S_{ij} - \frac{1}{3}S_{kk}\,\delta_{ij}\right) \quad (4)$$

where the strain rate S_{ij} is defined as follows

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \quad (5)$$

for an incompressible flow, S_{kk} in Equation 4 is zero.

$$S_{kk} = \frac{1}{2}\left(\frac{\partial U_k}{\partial x_k} + \frac{\partial U_k}{\partial x_k}\right) = \frac{\partial U_k}{\partial x_k}\frac{\partial U_k}{\partial x_k} = 0 \quad (6)$$

using the Reynold's decomposition, dividing the instantaneous speed U_i and the pressure P into an average and fluctuating component U, P, u”, p”.

$$U = \overline{U} + u'' \equiv u + u'' \quad (7)$$

$$P = \overline{P} + p'' \equiv p + p'' \quad (8)$$

The time average of a variable is defined as

$$\overline{\varphi} = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}\varphi dt \quad (9)$$

Using averaging properties, we obtain the continuity equation

$$\overline{\frac{\partial U_i}{\partial x_i}} = \frac{\partial \overline{U_i}}{\partial x_i} = \frac{\partial u_i}{\partial x_i} = 0 \quad (10)$$

Subtracting Equation 10 from Equation 2, we obtain that the fluctuating speed also follows the continuity equation

$$\frac{\partial u_i''}{\partial x_i} = 0 \qquad (11)$$

From the Navier Stokes equations over time we obtain:

$$\rho\frac{\partial U_i}{\partial t} + \rho\frac{\partial(U_j U_i)}{\partial x_j} - \rho R_i + \frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right) =$$

$$\rho\frac{\partial \overline{U_i}}{\partial t} + \rho\frac{\partial(\overline{U_j U_i})}{\partial x_j} - \rho\overline{R_i} + \frac{\partial \overline{P}}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right)\right) =$$

$$\rho\frac{\partial u_i}{\partial t} + \rho\frac{\partial(u_j u_i + \overline{u_j'' u_i''})}{\partial x_j} - \rho\overline{R_i} + \frac{\partial p}{\partial x_i} -$$

$$\frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$$

Assuming that the fluid is incompressible, the continuity equation is expressed as follows

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial(u_j u_i + \overline{u_j'' u_i''})}{\partial x_j} = \qquad (13)$$

$$\overline{R_i} - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(v\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$$

where v is the kinematic viscosity

$$v = \frac{\mu}{\rho} \qquad (14)$$

The turbulence model used in the simulations was the two-equation k-ω SST which uses the k-ω model in the boundary layer being the region that is dominated by viscosity and the k- E model outside this region. Thus, it provides more realistic flow solutions in the boundary layer which is achieved with a change function. For all simulations in this paper a high Reynolds number model or Wall Function was used, the value of y+ is dependent on the Reynolds number and consequently for high Reynolds numbers the higher this value should be. The calculation of this value was performed following the recommendations of Numeca [6] taking as reference the highest speed of the analysis.

$$y^+ = max\left\{y^+_{min}\ ; min\left\{30 + \frac{(Re - 10^6) * 270}{10^9}; y^+_{max}\right\}\right\}$$

Computational Domain

The computational domain was defined following the ITTC recommendations [2] for planing vessels Fig. 2, placing the boundaries far enough apart to avoid affecting the solution, the computational domain defined is four lengths aft, three lengths forward and three lengths to the side. In order to reduce the computational domain and computational time, the simulations were performed at half-length by applying the symmetry condition. Commonly, in drag simulations certain degrees of freedom are allowed to the rigid body, for the case of study pitching and heaving movements were allowed. These movements are significant in planing boats and therefore require meshing techniques that allow for high body movements without affecting the solution. The movement in the X axis of the rigid body was not allowed and the speed was imposed on the flow in the opposite direction to the motion in order to obtain the forces to which the body is subjected, thus obtaining the drag.

Deep Water Simulations

In these simulations, the computational domain was divided into two regions using Overset Mesh, which is used for bodies that undergo high motions. A base or subsequent stationary domain was generated, as well as a domain called Overset, which follows the rotation and other movements of the boat, generating an interpolation between the cells of these two domains during the simulation to obtain the solution.

Shallow Water Simulations

In shallow water simulations it is necessary to consider some physical effects that are negligible in deep water theory, particularly the viscous effects on the bottom and the rigid body, so the bottom boundary condition must be imposed as no-slip, causing a gradient in the flow speed to be generated. For such purpose, additional meshing layers are

Fig. 2. Domain and Boundary Conditions.

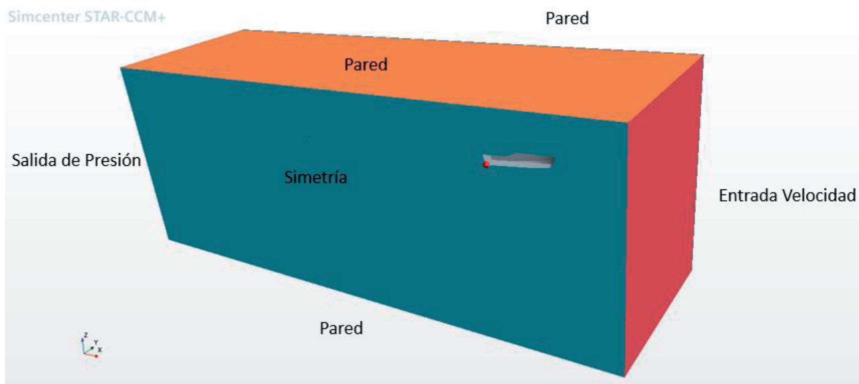
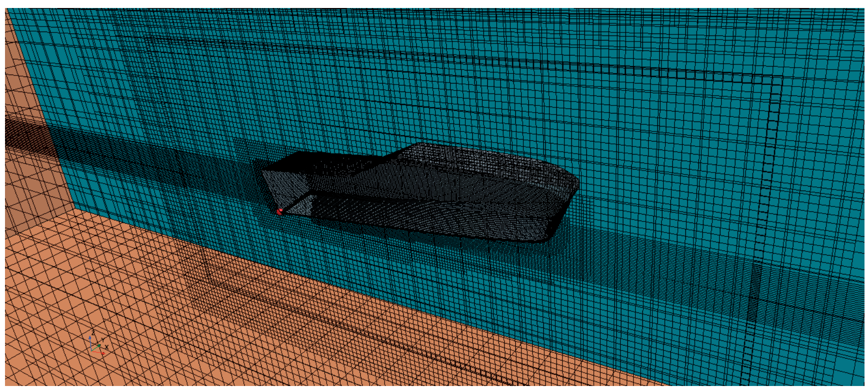


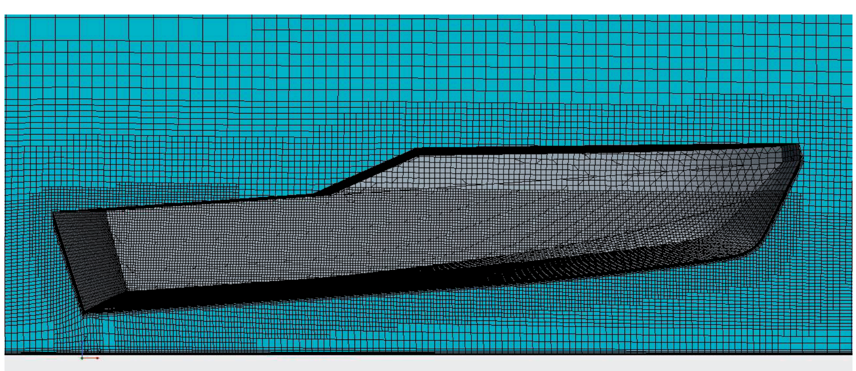
Fig. 3. Deep Water Meshing.



added on this boundary, thus increasing the total number of cells in the computational domain.

The definition of the meshing in Shallow Water is different from traditional drag simulations, considering the proximity of the boat to the bottom (computational volume limit), for this case the Overset Mesh cannot be used since due to the displacements of the rigid body, the moving region could be outside the base domain, preventing to obtain a solution. For this reason we used Morphing Mesh with a single region which allows the deformation of the mesh depending on the movements to which the rigid body is subjected.

Fig. 4. Shallow Water Meshing.



Influence on drag resistance due to shallow water

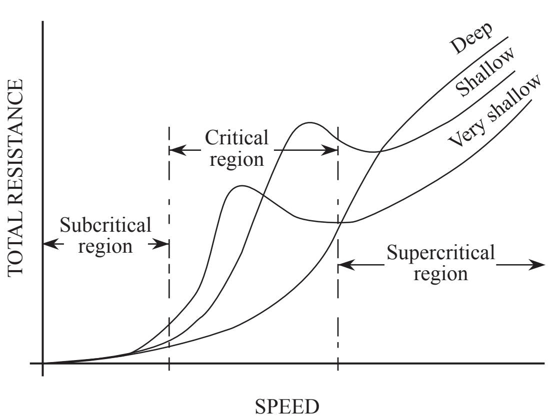
The drag in shallow water differs significantly from the drag in deep water and is therefore a determining factor in the design of this type of vessel. These drag effects are evidenced by the vessels based on their length-to-depth ratio *L/h*, therefore these boats experience them permanently during the normal course of their operations.

Experimental, theoretical and numerical simulation references indicate that these effects begin to appear at depth Froude numbers Equation 16 greater than 0.7, with a peak of maximum effect at a depth Froude number of 0.95 and persist up to Froude numbers of 1.2, identifying three regions of effect as shown in Fig. 16. 5 [3]:

$$F_{nh} = \frac{V}{\sqrt{gh}} \tag{16}$$

- Subcritical region: Where shallow water effects are negligible $F_{nh} < 0.7$.
- Critical Region: Where there is evidence of drag effect $0.7 < F_{nh} < 1.2$.
- Supercritical region: Where the drag effect is positive, reducing it and increasing speed $F_{nh} > 1.2$.

Fig. 5. Drag based on Speed and Depth [3].



The navigation area of these boats is characterized by the variation of their depth, with depths varying between 0.5 and 5 meters. Fig. 6 shows the subcritical, critical and supercritical regions based on speed and depth, evidencing that this vessel has a permanent drag effect when navigating in these regions and therefore it is a critical factor to comply with the contractual speed in all its operation areas.

Numerical simulations to assess drag were carried out at the depths shown in Table 2, where they are expressed in the length-to-depth ratio *L/h*.

Table 2. Simulation depths..

Depth (m)	L/h
0.8	8.84
1.0	7.07
1.3	5.44
1.75	4.04
2.5	2.83
3.25	2.18
4.0	1.77
22	0.32

Results of drag simulations

Simulations were performed on Star CCM+ using a 128-core @2.25GHz server. These were carried out for the depths mentioned above and speeds up to 21 knots. The results of the drag are shown in Fig. 7, which shows a considerable drag effect based on the depth, increasing significantly and running the characteristic peaks of the drag curve of planing boats at lower speeds with decreasing depth.

As mentioned above, one of the biggest challenges identified during the design of this vessel was to reach the maximum design speed of 15 knots, it is evident that the drag in deep water for this speed is similar to the drag obtained for significantly lower speeds at shallower depths; between 7 and 9 knots, and therefore it is of vital importance since the installed capacity was limited to 120 Hp, resulting in the risk that it would not be enough to exceed these drag peaks at all depths.

Fig. 6. Velocity-Depth curve with critical regions.

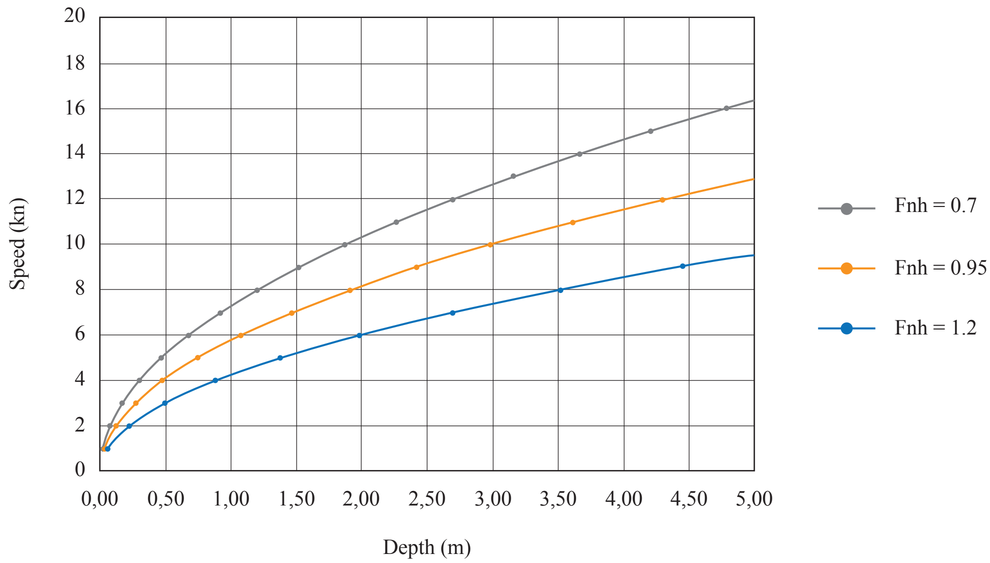
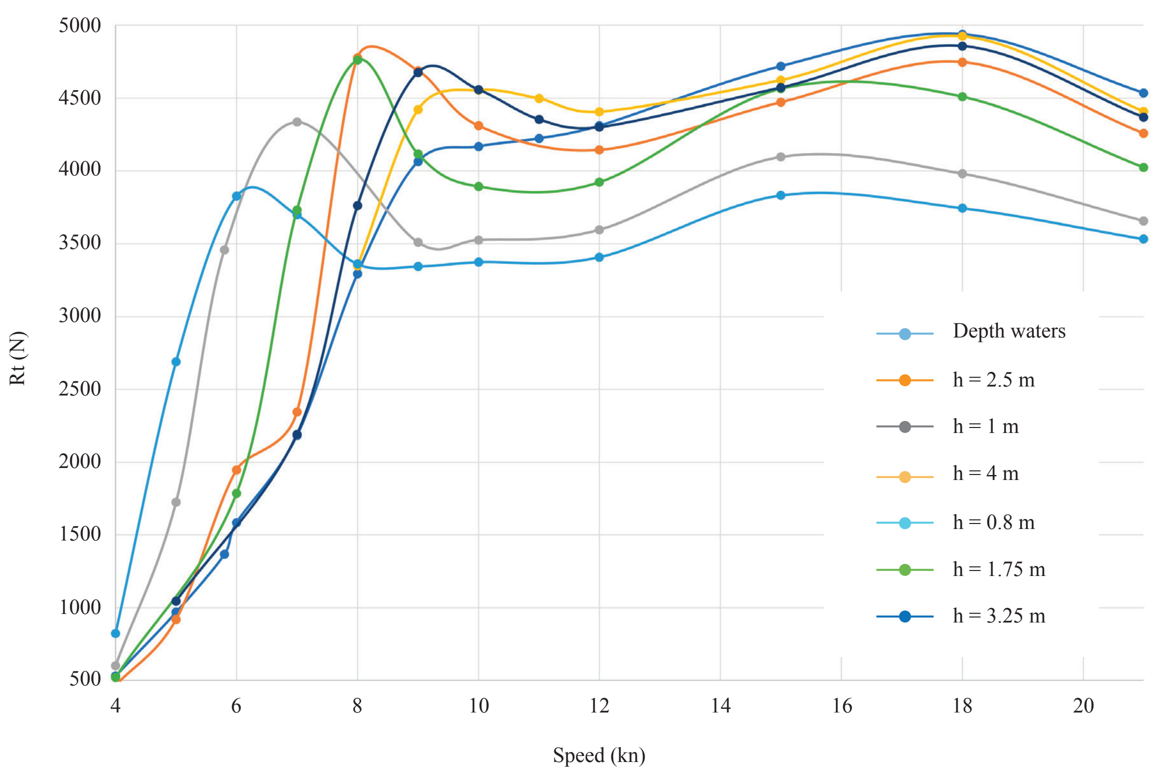


Fig. 7. Total Drag-Speed curve at different depths.



In order to guarantee this design speed, a prototype boat was built and subjected to performance tests at different depths, and a hydrodynamic optimization of the shapes was carried out, reducing the drag by 8% for the design speed. The drag was assessed for a total of 300 variations of the prototype hull using a semi-parametric variation of shapes, and the drag values correspond to the hull selected after applying an optimization process, which is not described in this paper. To further analyze the effect on shallow water drag, it is more convenient to plot drag based on Fnh to identify the subcritical, critical and supercritical regions. Fig. 8 shows that the greatest drag effect corresponds to the values mentioned in [3], reaching a greater effect at F_{nh} = 0.95. It is also evident that after the supercritical region a reduction in drag is obtained, which generates an increase in the final speed of the vessel when exceeding this region.

It is important to analyze the impact of the drag due to these phenomena, and it is convenient to separate the components of the total drag calculated by the numerical simulations to study them in detail. Separate monitors are used for viscous drag RV and residual drag RR. The increase in drag in shallow water is mainly due to residual drag, the effects on viscous drag can be neglected [3].

A convenient way to analyze the residual drag obtained in the simulations is to express it as the ratio between the residual drag in shallow water and deep water based on the F_{nh} number.

From Fig. 9 it can be observed, based on the ratio of shallow and deep water residual drag and the F_{nh} number, that the drag increase in the regions of distress due to shallow water effects is a function of the ratio of hull length to the depth *L/h*, as is the subsequent drag reduction when passing these regions as expressed by Millward in 1986, with a considerable increase in drag when this ratio has higher values in the critical regions [4]. In the experiments performed by Millward this ratio was limited to a value of *L/h* = 6, the simulations were carried out at a maximum value of *L/h* = 8.8 corresponding to a depth of 0.8 meters.

Wave pattern at different depths

Normally the characteristic wave pattern or Kelvin wave pattern is known; this pattern consists of two

Fig. 8. Total Drag-F_{nh} curve.

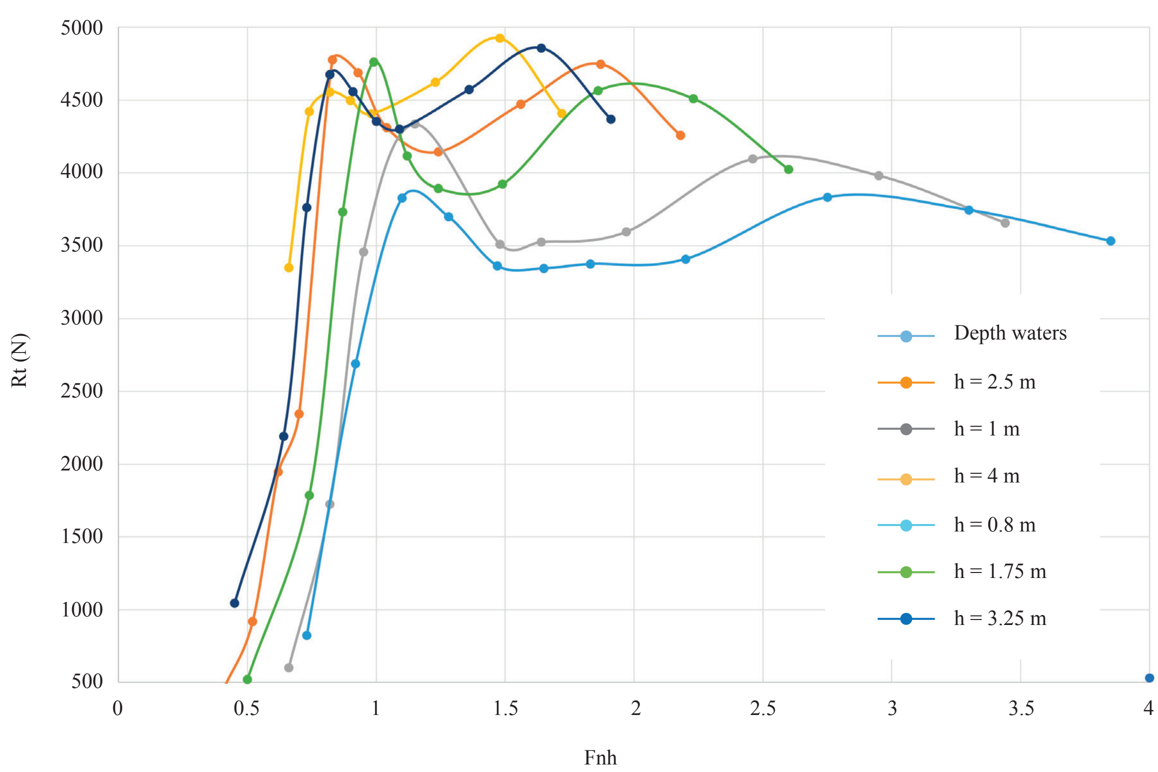
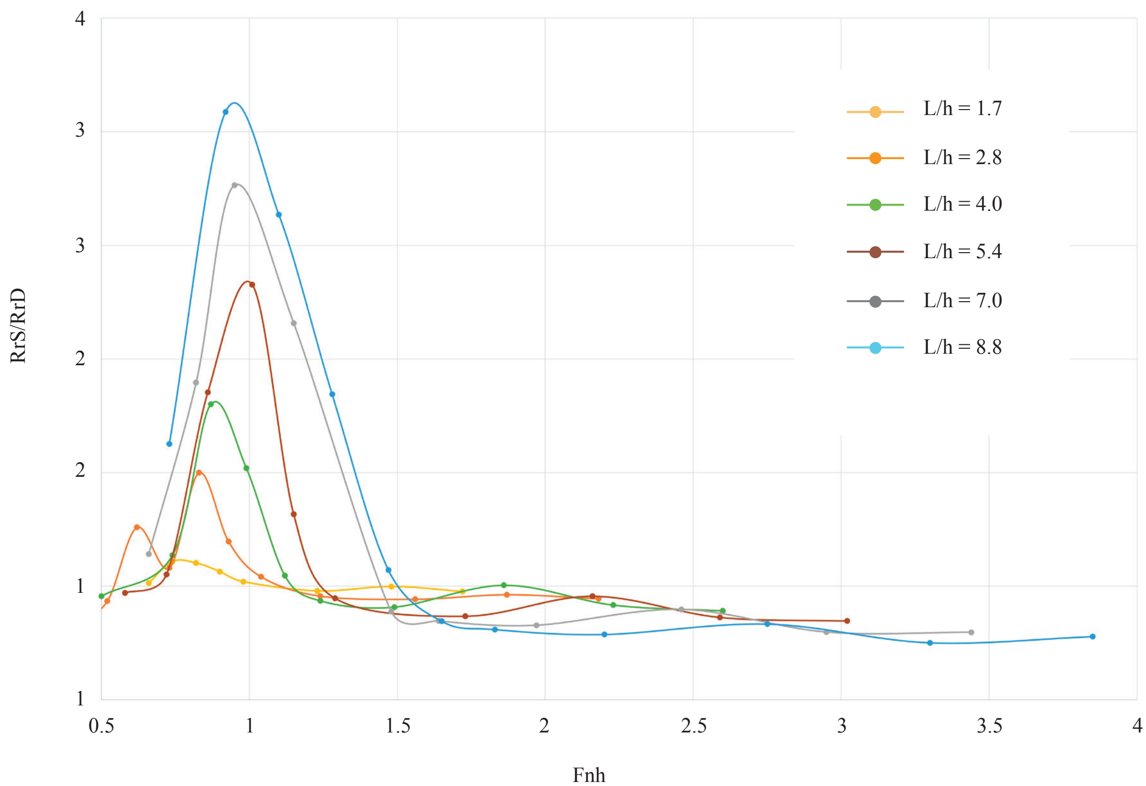


Fig. 9. Total Drag-F_{nh} curve.



groups of waves, the divergent and the transverse. The angle of the diverging bow waves is known with a value of 19º28', however this pattern is only valid for bodies sailing in deep and shallow waters with a number of $FF_{nh} < 0.4$ as shown in the Fig. 10. It is of great importance to analyze the wave pattern considering that the greatest impact on the drag is on the residual drag as mentioned above. This angle tends to increase as the F_{nh} number increases to a value of approximately 1.0, reaching angles up to 90º in which the waves appear to be traveling along with the hull. At this point all the energy is contained in the crest of the wave moving at the same speed of the vessel, observing only the transverse waves as shown in Fig. 11 [3].

Fig. 10. Wave pattern F_{nh} = 0.4.

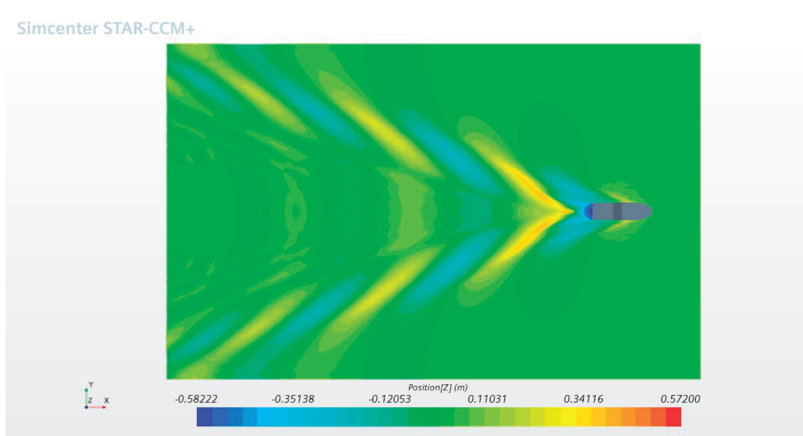


Fig. 11. Wave pattern $F_{nh} = 0.9$.

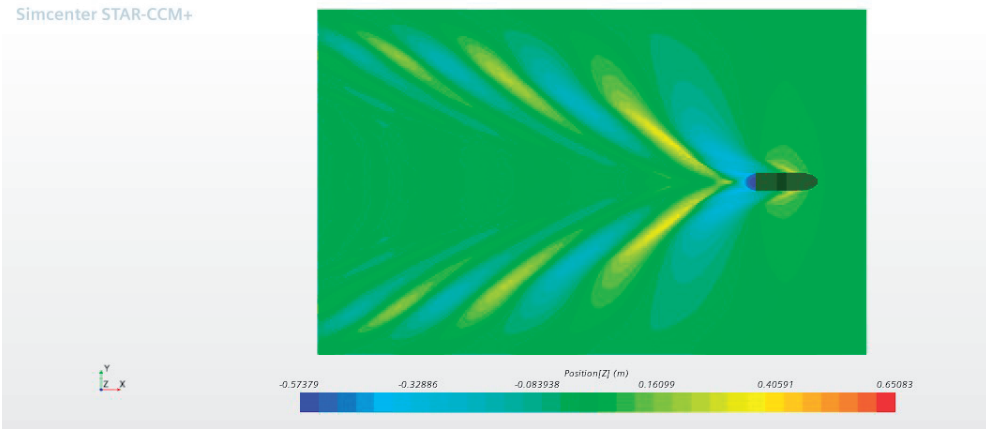
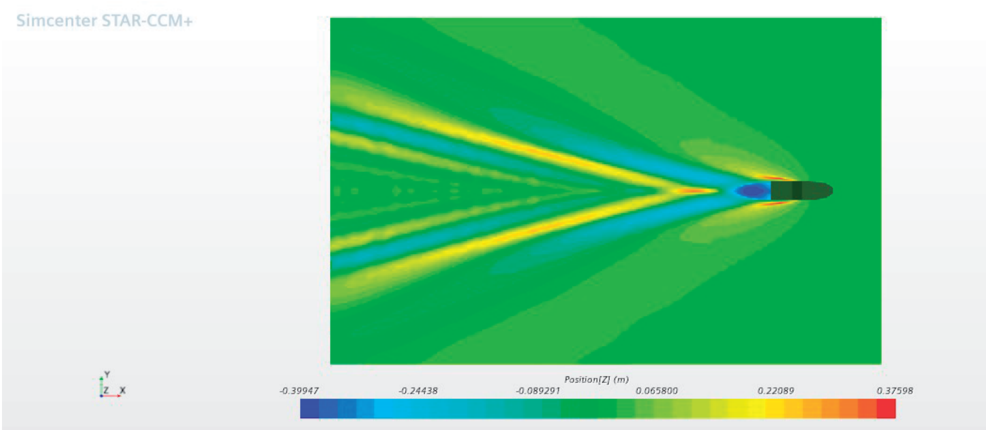


Fig. 12. Wave pattern $F_{nh} = 1.91$.



When the Fnh number is greater than 1, the angle of the diverging waves decreases considerably and transverse waves are not visible as shown in Fig. 12.

Conclusions

- In the simulations, the drag effect due to shallow water was evidenced, which is consistent with the numerical and experimental studies carried out on planing vessels affected by these events.
- It was evidenced that there is an area of increased drag which is found in the subcritical, critical and supercritical areas. This increase has a peak increase for a number of Fnh 0.9-1. After an Fnh number of 1.2 these effects diminish and generate an increase in the maximum speed of vessels.
- During the design phase, shallow water effects were taken into account, passing the maximum effect peaks at all speeds.
- It was evidenced that the shallow depth effect is mainly due to the drag caused by wave formation, residual.
- The pattern of waves and the energy contained in them varies depending on the L/h ratio. Having an increase in the angle of divergent waves which can be up to 90° in the critical area and a considerable reduction after this area.
- With this study we were able to determine the

drag and predict the maximum speed of the vessel in all its operating areas, being higher than the maximum design speed in all conditions.

- This study is of significant value because of the full-scale validation tests carried out, of which there are few references. These tests will be presented in a subsequent paper.

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[1] J. K. Author. (year, month day). Title (edition) [Type of medium]. Available: http://www.(URL)

Example:
[1] J. Jones. (1991, May 10). Networks (2nd ed.) [Online]. Available: http://www.atm.com

E-Mail

Basic form:
[1] J. K. Author. (year, month day). Title (edition) [Type of medium]. Available e-mail: Message:

Example:
[1] S. H. Gold. (1995, Oct. 10). *Inter-Network Talk* [Online]. Available e-mail: COMSERVE@RPIECS Message: Get NETWORK TALK

E-Mail

Basic form:
[1] J. K. Author. (year, month day). Title (edition) [Type of medium]. Available Telnet: Directory: File:

Example:
[1] V. Meligna. (1993, June 11). *Periodic table of elements* [Online]. Available Telnet: Library.CMU.edu Directory: Libraries/Reference Works File: Periodic Table of Elements

Patents

Basic form:
[1] J. K. Author, "Title of patent," U.S. Patent x xxx xxx, Abbrev. Month, day, year.

Example:
[1] J. P. Wilkinson, "Nonlinear resonant circuit devices," U.S. Patent 3 624 125, July 16, 1990.

Standards

Basic form:
[1] Title of Standard, Standard number, date.

Example:
[1] IEEE Criteria for Class IE Electric Systems, IEEE Standard 308, 1969.

Theses (M.S.) and Dissertations (Ph.D.)

Basic form:
[1] J. K. Author, "Title of thesis," M.S. thesis, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

Example:
[1] J. O. Williams, "Narrow-band analyzer," Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, 1993.

Unpublished

These are the two most common types of unpublished references.

Basic form:
[1] J. K. Author, private communication, Abbrev. Month, year.
[2] J. K. Author, "Title of paper," unpublished.

Examples:
[1] A. Harrison, private communication, May 1995.
[2] B. Smith, "An approach to graphs of linear forms," unpublished.

Periodicals

NOTE: When referencing IEEE Transactions, the issue number should be deleted and month carried.

Basic form:
[1] J. K. Author, "Name of paper," *Abbrev. Title of Periodical*, vol. *x*, no. x, pp. *xxx-xxx*, Abbrev. Month, year.

Examples:
[1] R. E. Kalman, "New results in linear filtering and prediction theory," J. Basic Eng., ser. D, vol. 83, pp. 95-108, Mar. 1961.

References

NOTE: Use *et al*. when three or more names are given.

References in Text:
References need not be cited in the text. When they are, they appear on the line, in square brackets, inside the punctuation. Grammatically, they may be treated as if they were footnote numbers, e.g.,

as shown by Brown [4], [5]; as mentioned earlier [2], [4]–[7], [9]; Smith [4] and Brown and Jones [5]; Wood et al. [7]

or as nouns:

as demonstrated in [3]; according to [4] and [6]–[9].

References Within a Reference:
Check the reference list for ibid. or op. cit. These refer to a previous reference and should be eliminated from the reference section. In text, repeat the earlier reference number and renumber the reference section accordingly. If the ibid. gives a new page number, or other information, use the following forms:

[3, Th. 1]; [3, Lemma 2]; [3, pp. 5-10]; [3, eq. (2)]; [3, Fig. 1]; [3, Appendix I]; [3, Sec. 4.5]; [3, Ch. 2, pp. 5-10]; [3, Algorithm 5].

NOTE: Editing of references may entail careful renumbering of references, as well as the citations in text.

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