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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 July 31st, 2023.

Receive a special greeting to the second edition of 2023 of our Science and Technology of Ships Magazine; after our successful VIII International Congress of Naval Design and Engineering - CIDIN held between March 8 and 10 in Cartagena de Indias.

In this space, created for the technology transfer with the objective to promote the development of the naval, maritime, and fluvial industry, we meet with our friends from academia and industry to share experiences and knowledge in innovation, advances, and technological developments specific to the sector, and in turn strengthen networks of scientific knowledge and commercial links.

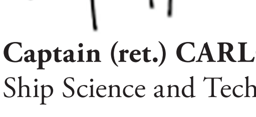
For this version, the main theme was Science, technology, and innovation for the sustainable development of the naval industry; and we develop 3 thematic axes: World trends applied to the design of naval vessels, Sustainable technological solutions applied to the naval, maritime, and fluvial industry and Opportunities and competitive bets of the shipyard sector through naval industry 4.0, for which we developed 49 presentations, 5 magisterial conferences and 3 academic forums, the latter with themes focused on How to improve operational effectiveness in naval designs, Proposals for the use of alternative energies in the naval, maritime, and fluvial industry and the analysis and Strategies to increase the competitiveness of the shipyard sector taking advantage of the digital transformation.

In this edition we present interesting articles on: Zero Pollution: design of a river tourist pontoon with electric propulsion based on hydrogen fuel cell, The great challenge of propeller cavitation in Shipbuilding - continuous control with the initiative Non-Intrusive Cavitation Detection System (Ni-CDS), Electrical design for efficiency: technical and operational measures for optimizing the use of electrical power in ships, Impacting factors on the accuracy of a fuel consumption measurement and Cybersecurity: a general framework in the maritime and military world.

We hope that this second semester will be full of successes and the culmination of their planned projects, see you in the next edition.

At COTECMAR, "We Keep Moving Forward"

Cordially,



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

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Nota Editorial

Cartagena de Indias, 31 de julio de 2023

Reciban un saludo especial a la segunda edición de 2023 de nuestra revista Ciencia y Tecnología de Buques; luego de nuestro exitoso VIII Congreso Internacional de Diseño e Ingeniería Naval – CIDIN realizado entre el 8 y 10 de marzo en Cartagena de Indias.

En este espacio de transferencia tecnológica creado para promover el desarrollo de la industria naval, marítima y fluvial, nos encontramos con nuestros amigos de la academia y la industria con el fin de compartir experiencias y conocimientos en innovación, avances y desarrollos tecnológicos propios del sector, y a su vez fortalecer las redes de conocimientos científicos y nexos comerciales.

Para esta versión el tema principal fue la Ciencia, la tecnología y la innovación para el desarrollo sostenible de la industria naval; y desarrollamos 3 ejes temáticos: Tendencias mundiales aplicadas al diseño de buques navales, Soluciones tecnológicas sostenibles aplicadas a la industria naval, marítima y fluvial y Oportunidades y apuestas competitivas del sector astillero a través de la industria naval 4.0, para los cuales desarrollamos 49 ponencias, 5 conferencias magistrales y 3 foros académicos, estos últimos con temáticas enfocadas en mejorar la efectividad operacional en los diseños navales, propuestas para el empleo de energías alternativas en la industria naval, marítima y fluvial y el análisis y estrategias para elevar la competitividad del sector astillero aprovechando las ventajas de la transformación digital.

En esta edición presentamos interesantes artículos sobre: Contaminación cero: diseño de una pontona turística fluvial con propulsión eléctrica basada en pila de combustible de hidrógeno, El gran reto de la cavitación de las hélices en la Construcción Naval - control continuo mediante la iniciativa Sistema No-Intrusivo de Detección de Cavitación (Ni-CDS), El diseño eléctrico para la eficiencia: medidas técnicas y operacionales para la optimización del uso de la potencia eléctrica en buques, Factores que influyen en la precisión de la medición del consumo de combustible y la Ciberseguridad: un marco general en el mundo marítimo y militar.

Esperamos que este segundo semestre sea para todos nuestros lectores, lleno de éxitos y la culminación de sus proyectos trazados, nos vemos en la próxima edición.

En COTECMAR, “Seguimos Avante”

Cordialmente,

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

Zero Pollution: design of a river tourist pontoon with electric propulsion based on hydrogen fuel cell

Contaminación cero: diseño de una pontona turística fluvial con propulsión eléctrica basada en pila de combustible de hidrógeno

DOI: https://doi.org/10.25043/19098642.238

David Naranjo Tabares [1]
José María Riola Rodríguez [2]

Abstract

Environmental logistics in Colombian river areas requires solutions that allow economic development based on tourism, without ecological degradation. Therefore, this paper shows the most relevant aspects of the project and preliminary design of a Pontoon-type vessel with a catamaran hull of 8 meters in length with enough power to reach a speed of 5 knots (85%MCR) and built in aluminum, which will also have electric propulsion based on a hydrogen fuel cell, and using renewable energies such as solar panels on the roof and a wind turbine. One of its main characteristics is that it will be a pollution-free ship and its classification will be done following the regulations of the Bureau Veritas, and all those national and international regulations that are applicable. Due to the problems generated by the daily use of the different means river transportation, which undoubtedly, could generate an irreversible affectation to the environment and a considerable loss of biodiversity in aquatic ecosystems, which worsens over time, this prototype design might be presented to national shipbuilding, as a possibility for designing eco-friendly tourist vessels for the country's river areas, as an example for future constructions that are expected with the rise of tourism in the country.
Key words: Naval Architecture, Design, Hydrogen fuel cell, Pontoon, Catamaran, Environment.

Resumen

La logística medioambiental en las zonas fluviales colombianas requiere soluciones que permitan el desarrollo económico basado en el turismo, sin degradación ecológica. Por ello, esta investigación muestra los aspectos más relevantes del proyecto y el diseño preliminar de una embarcación tipo Pontona con casco catamarán de 8 metros de eslora con la potencia suficiente para alcanzar una velocidad de 5 nudos (85%MCR) y construida en aluminio, que además cuente con propulsión eléctrica basada en una pila de combustible de hidrógeno, y utilizando energías renovables como paneles solares en la cubierta y un aerogenerador. Una de sus principales características es que será una embarcación libre de contaminación y su clasificación se hará siguiendo la normativa del Bureau Veritas, y todas aquellas normativas nacionales e internacionales que sean de aplicación. Debido a la problemática que genera el uso cotidiano de los diferentes medios de transporte fluvial, que sin lugar a dudas, podría generar una afectación irreversible al medio ambiente y una pérdida considerable de biodiversidad en los ecosistemas acuáticos, que se agrava con el paso del tiempo, este prototipo de diseño podría ser presentado a la construcción naval nacional, como una posibilidad de diseño de embarcaciones turísticas ecológicas para las zonas fluviales del país, como ejemplo para futuras construcciones que se esperan con el auge del turismo en el país.
Palabras claves: Arquitectura naval, Diseño, Pila de combustible de hidrógeno, Pontona, Catamarán, medio ambiente.

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Introduction

In 2019, the tourism sector was the second largest generator of foreign exchange in the country, and the national government began to invest several efforts in it, to arouse the interest of businessmen and investors from all over the world, expecting a special boom in tourists in regions with river areas in the country, with high environmental interest *(Santoro, 2019)*. Considering that situation, it is important to invest in research and development of products that enhance tourism in the country, while adequately protecting the environment. The main function of the tourist pontoon to be designed is the performance of tourism functions in the rivers located in regions with high ecological value, that are protected from contamination. For example, one of the rivers where the project can be implemented is the Bita river, which is protected in Colombia. Here, the State and other social actors must take measures before the water resources suffer irreversible damages, including the loss of species that benefit from that specific environment, such as jaguars, dolphins, giant otters, turtles and "arawanas" *(Colprensa, 2015)*. This is one of the fundamental missions for both the Colombian National Navy and the different tourism companies, that seek compliance with standards that protect these pollution-free areas.

Hydrogen abounds on Earth and could be produced in quantities that satisfy demands of all means of transportation. If it is produced through renewable energies, it could be the fuel of the coming decades. Fuel cells are directly associated with hydrogen, and propulsion systems based on them appear to be the most immediate clean solution to fuel alternatives.

This project seeks to implement an electric propulsion solution based on a hydrogen fuel cell, which is also able to operate in rivers located in protected areas of the country. For this development, the physical and chemical properties of hydrogen, its production, storage systems, the operating principle of fuel cells *(Balbona, 2014)* and all relevant studies for the design of the vessel must be covered, such as, hydrostatic curves, structural calculations and ship weight, design of electrical generation and distribution, and the design of propulsion and auxiliary systems. These bases must be clearly reflected due to the importance of hydrogen technologies *(Valdés et al, 2018)*, being essential in the future of electricity production to solve the problem of greenhouse gas emissions, and particularly CO_2, which causes huge environmental damages.

Fuel Cell

According to the National Center for Experimentation of Hydrogen Technologies and Fuel Cells of Spain (CNH2), a fuel cell (FC) is an electrochemical device that transforms chemical energy directly into electricity. It starts with a fuel, usually hydrogen, and an oxidant, in many cases oxygen, to produce water, electricity in a continuous electric current and heat. In those fuel cells that consume hydrogen (H_2) or which contain a proton exchange membrane or Proton Exchange Membrane Fuel Cell (PEMFC), the current is generated from the reaction shown in the following equation (1) *(Leo, 2008)*.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1}$$

The fuel is H_2 and the O_2 would be supplied by the air. It should be clear that it is not an H_2 combustion reaction, but rather, an electrochemical process consisting of oxidation-reduction reactions, in which the energy released by the spontaneous reaction is converted into electricity and electrical energy and can be used to make a non-spontaneous reaction occur; requiring electrochemical techniques and microbial fuel cells *(Peña, et.al., 2020)*. FCs are not heat engines; therefore, their operation is not limited by the Carnot yield. Equation (2) shows how hydrogen decomposes at the anodes according to the oxidation reaction and equation (3) shows the reduction at the cathode.

$$H_2 \rightarrow 2H^+ + 2\,e^- \tag{2}$$

$$\frac{1}{2}O^2 + 2\,H^+ + 2\,e^- \rightarrow H_2O \tag{3}$$

Fig. 1. Types of fuel cells and main characteristics.

	Operating temp. (°C)	Fuel	Electrolyte
PEMFC	40-90	H_2 (/CO_2)	Polymer
AFC	40-200	H_2	KOH
DMFC	60-130	Methanol	Polymer
PAFC	200	H_2 (/CO_2)	Phosphoric Acid
MCFC	650	CH_4, H_2, CO	Molten Carbonate
SOFC	600-950	CH_4, H_2, CO	Solid Oxide

Noble Metals

Noble Metals/ non-noble metals

Non-noble metals

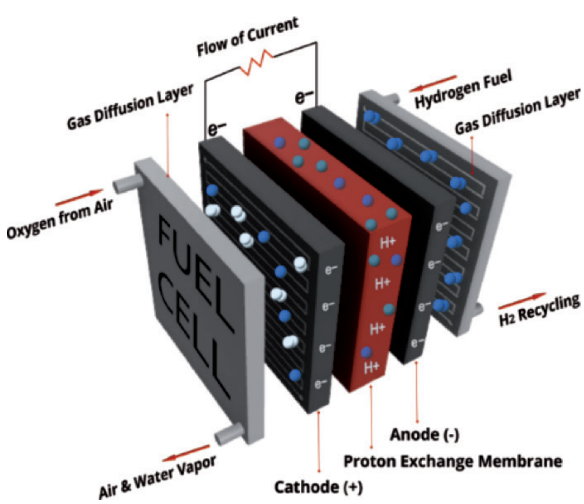
Source: Fuelcells, earthsci.org, s.f.

These equations depend on the type of applications for fuel cells. That is, variables such as chemical reactions, the type of catalysts required for the reaction to take place, the range of operating temperatures of the cell and the fuel required, have a direct impact on their applications. *(CNH2, 2020).*

Fig. 1 shows the different types of fuel cells.

These fuel cells present great results such as high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. Fig. 2 shows an example of a fuel cell diagram, and Fig. 3 (see page 12) shows that the efficiency of the cell is little dependent on the size of the system, which allows, in addition to its use in different energy ranges, the design of modular fuel cell systems. Furthermore, they can operate at half load while maintaining optimal fuel usage.

Fig. 2. Solid oxide fuel cell scheme.



Source: Roca, 2021.

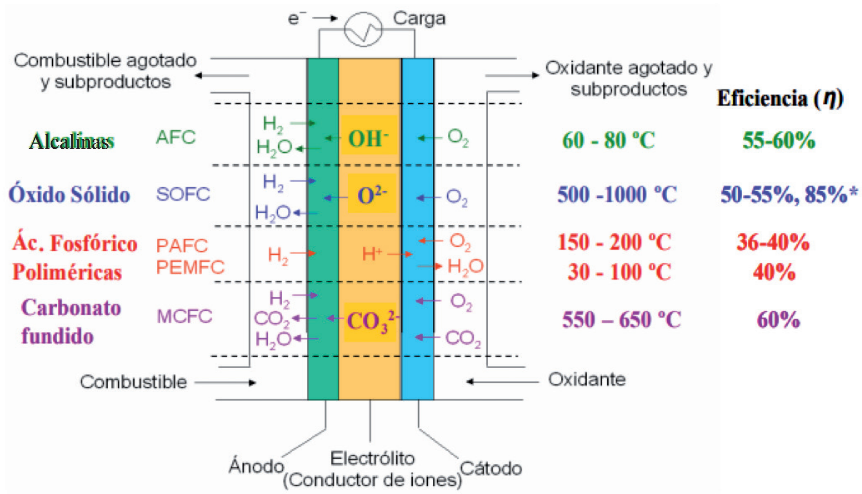
Tourist Pontoon design

The design process of the vessel was carried out with the support of the concept of the design spiral (Fig. 4), as a guide to achieve a single result.

This is the development of the vessel through an optimal and effective process, following an established order which must be respected. Thus, the design tool ensures the adequate proportion and balance of the project. Its viability, approximate budget, fundamental specifications such as its useful life, speed, passenger and crew capacity, vessel limits and type of propulsion were determined. Legal and safety regulations were also identified and applied during the planning of the project.

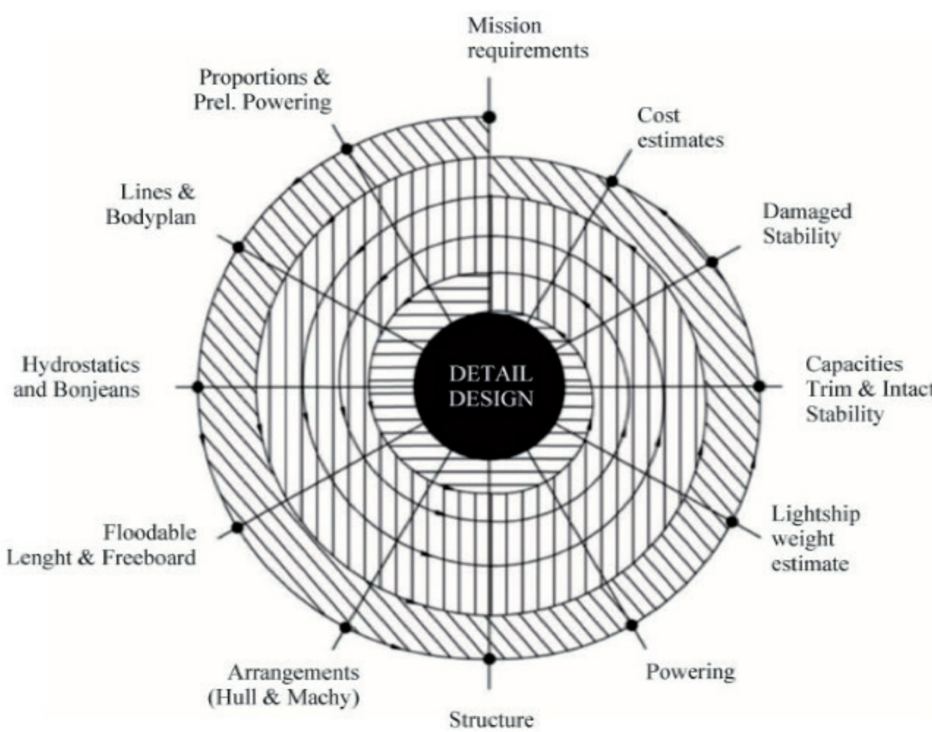
The aim is for the boat elaboration to be accepted by the nation official entities. Finally, the intention is to present a product ready for construction, with plans that comply with all the legal safe-conducts to allow the project to be executed without any impediment, as shown in Fig. 5.

Fig. 3. Types of fuel cells.



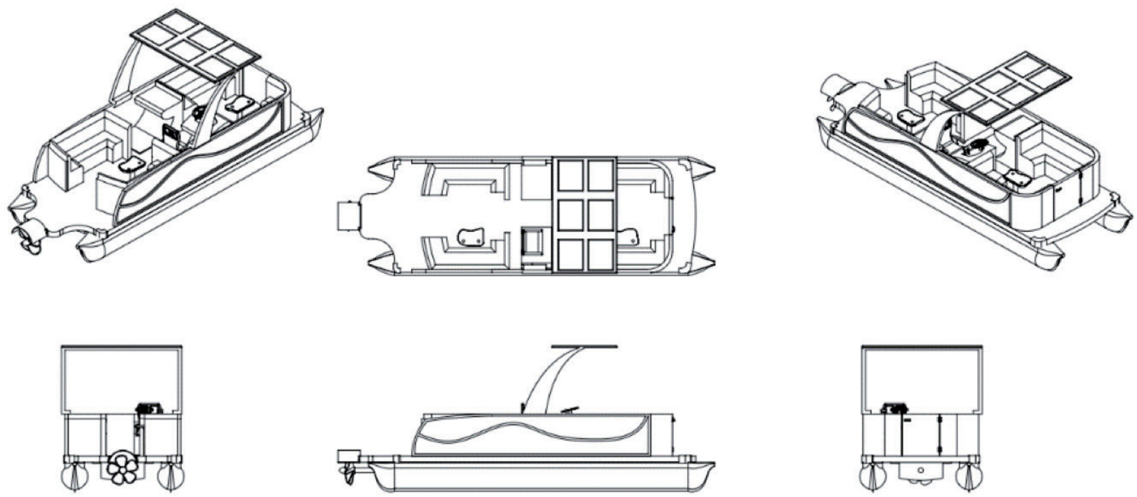
Source: Merino, s.f.

Fig. 4. Design spiral.



Source: Richard, 2019.

Fig. 5. 3D tourist pontoon design.

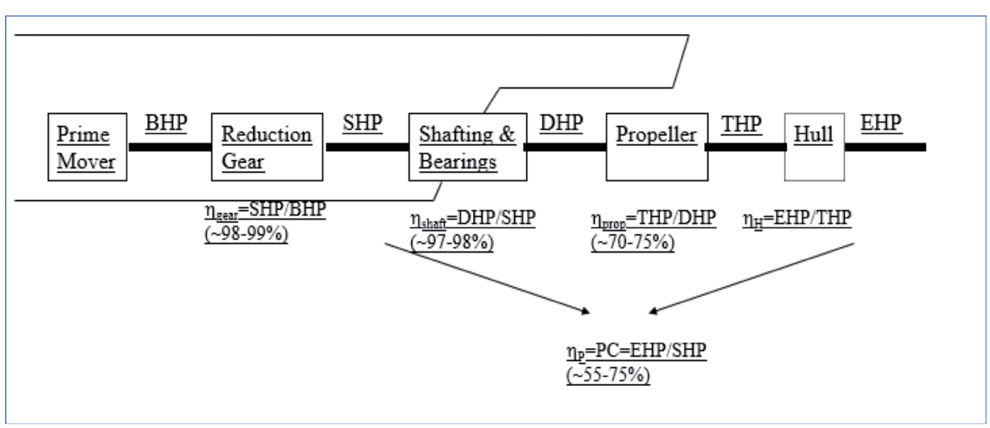


Source: Own source.

For the design of the boat, the Maxsurf Modeler Advanced software was used, especially in the design of shapes and hydrodynamic optimization of Catamaran-type hulls. The Maxurf Resistance and Masurf Stability Advanced for the studies of stability and behavior at sea, and Rhinoceros in the 3D CAD design, where the habitability services and amenities are evidenced were also used. A technological surveillance study was carried out regarding which fuel to use based on the hydrogen vector *(Cifuentes el at, 2019)*, considering the powers needed for a tourist ride, compressed hydrogen would be the fuel used. This simplifies possible logistical problems of some other possible e-fuels.

Because of the need to optimize the life cycle of the ship *(Fdez-Jove et al, 2018)*, to calculate the propulsion system based on the hydrogen cell, the values of the system performances were provided by the United States Naval Academy *(USNA, 2001)*, Fig. 6.

Fig. 6. Propulsive efficiency.

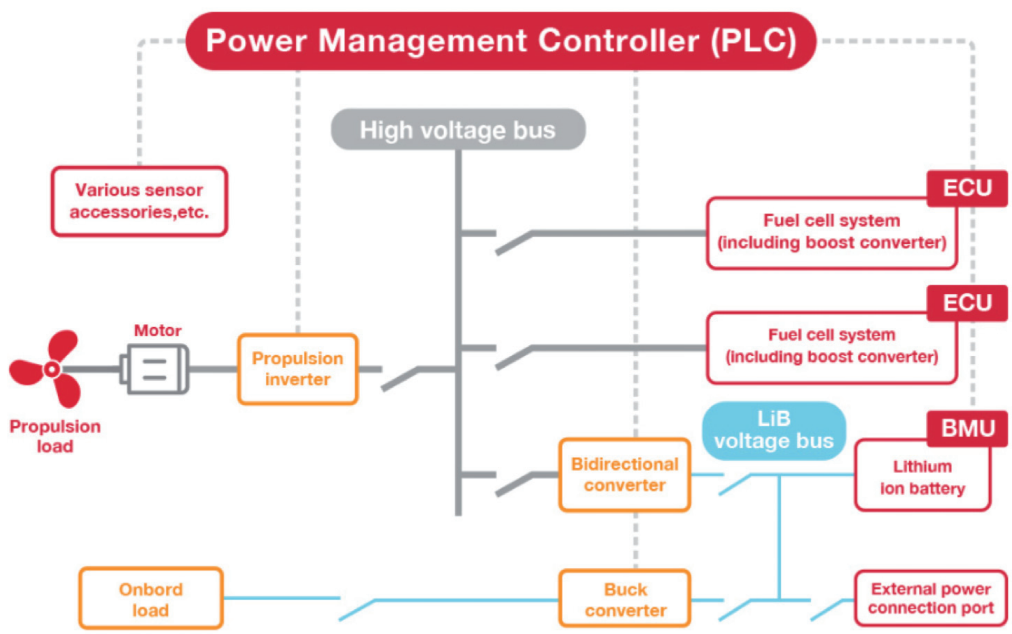


Source: USNA.

Propulsion System and Power Management

The implementation of the battery-based propulsion, based on hydrogen fuel in other types of vessels such as the Hynova 40, had to be analyzed and tested in the Energy Observer, called REXH2 (Range Extender Hydrogen), *(Choloé Torterat, 2020)*, the Ma-Hy-Hy projects (Marine Hydrogen Hybrid) , *(Briag Merlet, 2022)*, the YANMAR vessel, Fuel Cell supported by Toyota Motor Corporation, *(Yanmar Holdings, 2021)*. Data of the operation of the hydrogen fuel cell system and the control of the electric power train during real tests at sea and river areas were collected, evidencing an energy management system that coordinates and controls the operation of the fuel cells, lithium ion batteries and motors *(Guerrero, 2022)*. Fig. 7 shows it in detail.

Fig. 7. Power Managment Controller.

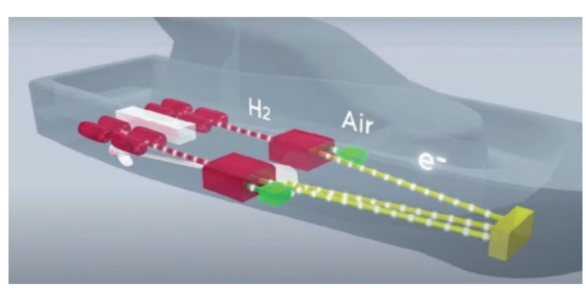


Source: Yanmar Holdings, 2021.

Propulsion system distribution based on hydrogen fuel cell implemented in the tourist pontoon to navigate rivers in Colombia within protected areas would be as is shown in Fig. 8.

The selection of the fuel cell type was made searching in the supplier market and a PEM type fuel cell was selected, which has a power range of 0 to 250 KW and which is mainly used to feed transportation systems.

Fig. 8. Propulsion system distribution



Source: Rock, 2021.

Autonomy

The polarization (V) of the fuel cell *(Ramírez et al, 2022)* is the voltage between the electrodes and is given by the expression shown in equation 4:

$$V = N\,(VAC - Re\,Di - PT\,Ln\,Di - C_1\,e^{Di\,C_2}) \quad (4)$$

Where
N: number of cells in the stack
VAC: open circuit volts
Re: specific resistance
Di: current density
PT: slope of Tafel or graphical representation of a straight-line portion of a polarization curve
C_1 and C_2 are constants

The battery power in watts responds to the expression shown in equation 5:

$$P = \eta\,V\,Di\,S \quad (5)$$

where η is the yield and *S* the cell area.

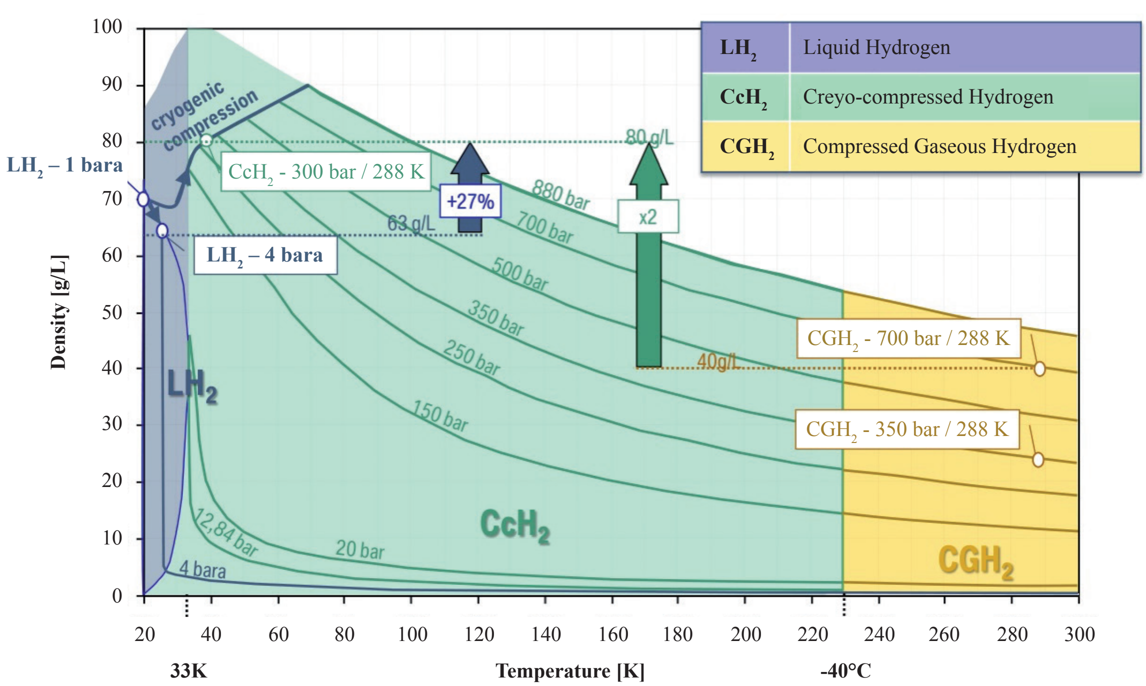
Amount of hydrogen in kilos required for the PEM-type fuel cell in stack. The following equation (6) is applied in which the following variables must be known:

$$\text{Amount of hydrogen} = \frac{P\,T}{\eta\,LHV} \quad (6)$$

P= power delivered by the batteries in kW
T= operating time in hours
η= performance of the PEM type battery 0.53%
LHV=lower heating value of hydrogen, 120 MJ/Kg

Commercial cylinders dimensions managed by the company Marine Service Nord *(Barón et al, 2022*), which comply with the safety standards established by SOLAS (International Convention for the Safety of Life at Sea) were taken as a reference. With the height and diameter of the cylinders, the formula for calculating the volume of a cylinder was used to know the volumetric capacity of each commercial cylinder. With this volume, the variables density and temperature are derived from the pressure. In

Fig. 9. Hydrogen density-temperature diagram.



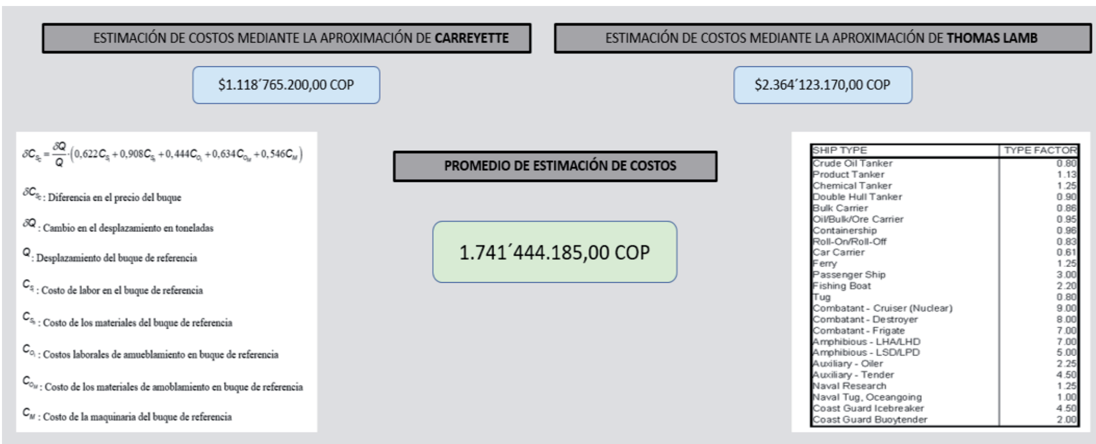
Source: AEH, 2019.

this case, 700 bar is referenced as the maximum pressure that each type IV commercial cylinder can withstand and thus, the mass of each cylinder. So, for the storage of compressed hydrogen, in a bottle along the length, the conditions were established at 700 bars and 15°C. Fig. 9 is an example of this.

Costs

The costs of the exposed project are reflected in the following table (2):

Table 2. Cost analysis.



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$$\delta C_{S_C} = \frac{\delta Q}{Q} \cdot \left(0,622 C_{S_L} + 0,908 C_{S_M} + 0,444 C_{O_L} + 0,634 C_{O_M} + 0,546 C_M\right)$$

δC_{S_C} : Diferencia en el precio del buque

δQ : Cambio en el desplazamiento en toneladas

Q : Desplazamiento del buque de referencia

C_{S_L} : Costo de labor en el buque de referencia

C_{S_M} : Costo de los materiales del buque de referencia

C_{O_L} : Costos laborales de amueblamiento en buque de referencia

C_{O_M} : Costo de los materiales de amoblamiento en buque de referencia

C_M : Costo de la maquinaria del buque de referencia

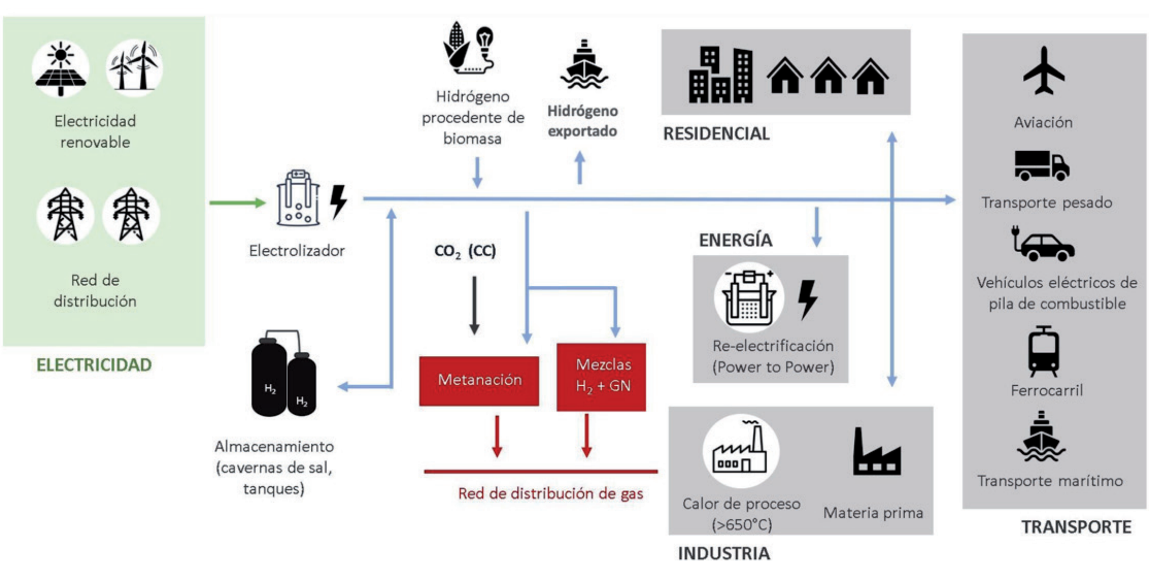
SHIP TYPE	TYPE FACTOR
Crude Oil Tanker	0.80
Product Tanker	1.13
Chemical Tanker	1.25
Double Hull Tanker	0.90
Bulk Carrier	0.86
Oil/Bulk/Ore Carrier	0.95
Containership	0.96
Roll-On/Roll-Off	0.83
Car Carrier	0.61
Ferry	1.25
Passenger Ship	3.00
Fishing Boat	2.20
Tug	0.80
Combatant - Cruiser (Nuclear)	9.00
Combatant - Destroyer	8.00
Combatant - Frigate	7.00
Amphibious - LHA/LHD	7.00
Amphibious - LSD/LPD	5.00
Auxiliary - Oiler	2.25
Auxiliary - Tender	4.50
Naval Research	1.25
Naval Tug, Oceangoing	1.00
Coast Guard Icebreaker	4.50
Coast Guard Buoytender	2.00

Source: Own source.

Conclusions

- The hydrogen society is knocking at the door (Fig. 11), Colombia must promote R&D programs to integrate hydrogen logistics within its technologies as soon as possible.

Fig. 11. Hydrogen society.



Source: AEH, 2019.

- This work focused on demonstrating that in tourism logistics, it is possible to design boats to enjoy the rivers richness in the regions of the country without producing pollution. For instance, the Bita River, which is a tributary of the Orinoco River, and is in Puerto Carreño with an extension of 500 kilometers and considered one of the healthiest rivers in the country, *(Colprensa, 2015)*.

- In accordance with the above, and as an example of the importance of this research, in 2022, the Colombian Ministry of Commerce, Industry and Tourism registered 15,871,329 domestic passenger arrivals, 3,303,582 international arrivals, 1,615,355 non-resident foreign visitors, 80,565 active tourism service providers in RNT (national register of tourism) and 58,896 cruise ship passengers, demonstrating that one of the main attractions is the biodiversity and fauna of Colombia, which generates a great business opportunity for the pontoon proposed in this article, *(Díaz, 2023)*.

- Currently, the hydrogen economy is not mature enough to compete with fossil fuels. But it is a solution that prevents the accumulation of CO2 in the atmosphere and contributes to reduce climate change on the planet. The use of hydrogen as an energy source provides a reduction in emissions, polluting substances and the greenhouse effect.

- From the research development, it can be stated that hydrogen could be a perfect alternative fuel for this type of tourist vessel. And the fact that its use as an energy vector reduces the emissions of polluting substances and its silent operation, presents an optimum solution for propulsion in areas of enormous environmental value, such as the regions located in river areas in the country.

- The main obstacle with the use of hydrogen in ship's, is that because of its low density, it occupies a significant amount of volume. Hence, for a single hydrogen pipe to be used per operation day, the speed of the boat shouldn't exceed the 5 or 6 knots, speed wich is enough for a leisure or turistic boat.

- The design of this prototype of a ship with alternative fuel sources, is attractive do to the high interest within the ship market for ships displacing less than 100 tons, primarily like touristic riverine vessels, barges and river boats working in rivers, for whom hydrogen offeers enourmous environmental benefits.

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The great challenge of propeller cavitation in shipbuilding. Continuous control with the innovative Non-Intrusive Cavitation Detection System (Ni-CDS)

El gran reto de la cavitación de las hélices en la Construcción Naval. Su control en continuo mediante el novedoso Sistema No-Intrusivo de Detección de Cavitación (Ni-CDS)

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Abstract

Cavitation is an unwanted phenomenon that has been present for more than 50 years in any ship propulsion system. Despite the great technological advances with the use of advanced simulation tools (CFD's), and new technology, we are still far from being able to eliminate it from propellers due to its own operating principle. This phenomenon will continue to occur under certain conditions of operation of the propulsion system of ships.
The consequences of this phenomenon are well known to the Navies, shipowners and naval engineers: reduction of the service life of the propeller and sometimes of the rudder and hull too, reduction of propulsive efficiency, a significant increase in vibrations and noise on board and, consequently, a reduction in comfort conditions and stealth capacity, together with noise pollution with negative effects on the oceans and marine fauna. This issue has been on the table at the IMO since 2008, currently working on updating MEPC.1/Circ.833. For this purpose, a working group of more than 120 experts from 40 entities (countries and organizations) from all over the world has been created, being TSI one of its most involved members.
After more than 5 years of research, TSI has developed the first non-intrusive system capable of automatically and continuously detect this phenomenon and quantify its intensity, with sufficient precision to provide valuable information for its control. By having a visible and real time indicator of this phenomenon, we can act and reduce the negative effects of cavitation and control the acoustic signature of our vessel at all times.

Key words: Cavitation, Monitoring, Efficiency, URN, Noise, Vibrations.

Resumen

La cavitación es un fenómeno no deseado que ha estado y está presente desde hace más de 50 años, en cualquier sistema de propulsión de los buques. A pesar de los grandes avances tecnológicos con el empleo de herramientas avanzadas de simulación (CFD´s), nuevas tecnologías y procesos de diseño y fabricación, aún estamos lejos de poder eliminarlo de las hélices debido a su propio principio de funcionamiento. El fenómeno de cavitación se va a seguir produciendo en determinadas condiciones de calados y operación del sistema propulsor de los buques.
Las consecuencias directas de este fenómeno son bien conocidas por las Armadas, armadores e ingenieros navales: reducción de la vida útil de la hélice y a veces también el timón y el casco, reducción de rendimiento propulsivo, un aumento significativo de las vibraciones y ruidos a bordo y, en consecuencia, disminución de las condiciones de confort y de la capacidad de sigilo, junto con una contaminación acústica con efectos negativos en los océanos y sobre la fauna marina. Esta problemática se encuentra en la mesa del IMO desde 2008, organismo internacional que actualmente está trabajando en la actualización de la MEPC.1/Circ.833. A tal efecto, se ha creado un grupo de trabajo de más de 120 expertos, de 40 entidades (países y organizaciones) de todo el mundo, siendo TSI uno de sus miembros más involucrados.
Tras más de 5 años de investigación, que comenzó en el marco del Proyecto AQUO "Achieving Quiet Oceans", financiado por el 7mo Programa Marco de la Unión Europea, TSI como PYME española ha desarrollado y lanzado al mercado el primer sistema no intrusivo capaz de detectar automáticamente y en continuo este fenómeno desde su inicio y cuantificar su intensidad, con suficiente precisión para proporcionar así una información muy valiosa para su control. Al tener un indicador visible y en tiempo real de este fenómeno, podemos actuar y reducir los efectos negativos de la cavitación y controlar la firma acústica de nuestro buque en todo momento.

Palabras claves: Cavitación, Monitoreo, Eficiencia, URN, Ruido, Vibraciones.

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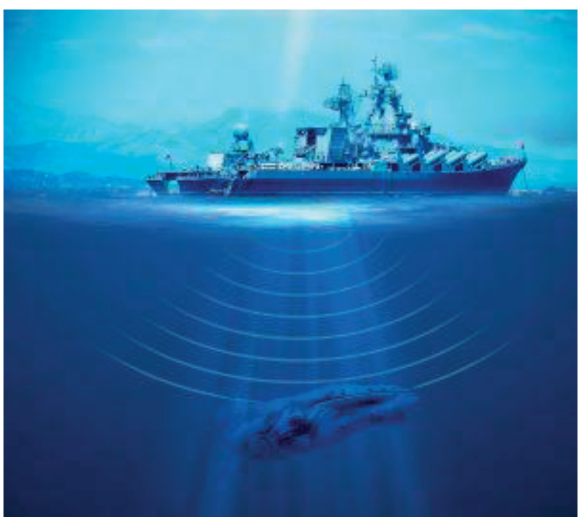
Introduction

The undesirable phenomenon of cavitation has represented in recent years one of the greatest challenges for modern naval engineering, giving rise to problems ranging from reliability, performance, to its impact on both the ship (noise and vibrations) and the marine environment (acoustic signature and "stealthy").

The noises radiated by ships into the marine environment coincide with those used by a large number of marine species for orientation and mating, mainly species such as cetaceans and other marine mammals. In addition to these aspects, the various regulatory bodies are giving increasing importance to reduce the noise emitted by the ships, preparing to regulate them strictly in the not-too-distant future.

Fig. 1. URN and marine lifeforms.



TSI, within several R&D projects, has been working, in the last five (5) years, in the development of a non-intrusive cavitation detection system that allows to know, in a simple, effective and real time way, when and how cavitation occurs in ships as well as its severity making possible to adapt the operating conditions of their ships and prevent cavitation from occurring.

Thanks to the application of this technology, ships will have a much easier way to adapt to the new requirements, while avoiding damage to the marine environment in the areas where they sail.

State of the Art

What is the cavitation?

Definition

The basic function of a propeller on a ship is to move it, transforming the power and torque coming from the main propulsion engines into thrust in the proper direction and direction. To achieve this effect, propellers, when turning, produce a pressure gradient on their blade faces. While on the rear face (pressure face) there is a pressure rise, on the opposite face, the front face (suction face), there is a noticeable pressure drop.

It is the combination of these pressure gradients that results in thrust, which is used to move the vessel, but, at the same time, if the speed of rotation of the blades reaches excessive values, on the face where the pressure drop occurs (suction face) the water can reach the vapor pressure, boiling at the ambient temperature. When the bubbles of steam separate from the surface of the blade dragged by the flow, they are exposed again to the normal pressure of the medium, collapsing violently and, consequently, generating pressure pulses and high levels of random broadband noise that are very harmful, both for the surrounding environment,

Fig. 2. Water P-T graphic.

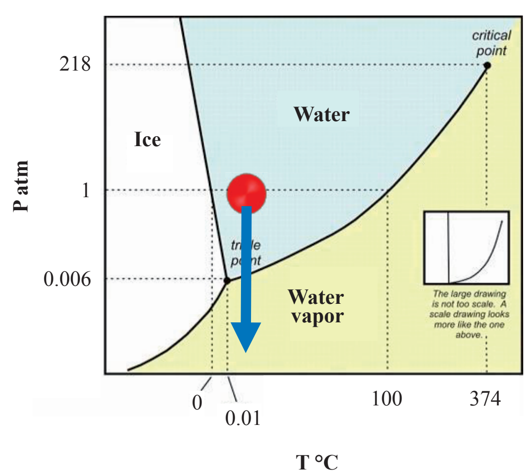
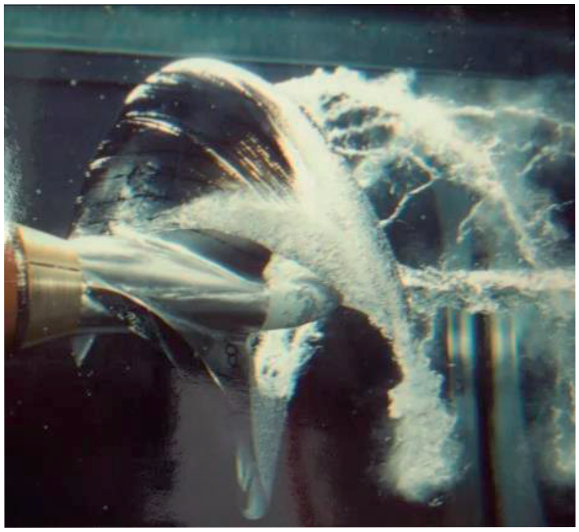


Fig. 3. Cavitation in naval propeller.



the propeller itself and the comfort of the ship. Figs. 2 and 3 shows the Cavitation Phenomena [3] .

This is the phenomenon known as cavitation, which, from a more technical point of view, can be defined as the hydrodynamic effect produced by the creation of water vapor bubbles at ambient temperature, as a result of the strong pressure gradients produced in the propeller of a ship, following Bernoulli's law.

Types of cavitation

Within the cavitation phenomenon, there are different types, which can be differentiated in a simple way by how they are produced, and in which areas of the propeller appear:

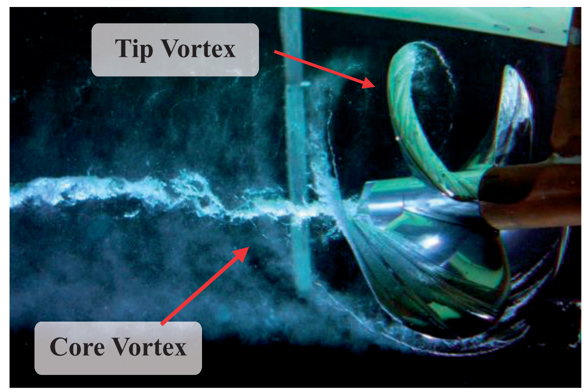
- ***Vortex cavitation:*** this type is subdivided into two main groups:

  Blade tip vortex cavitation: as the propeller blades rotate, flow vortex is produced starting from the high-pressure face at the tip of the blades, and ending in the suction face. In the center of these vortex, the flow can reach very high velocities, which together with the general pressure depression produced by the blades, cause the appearance of this type of cavitation.

  Core vortex cavitation: similar to the previous one, but produced by the confluence of the vortex that originate at the roots of the blades and converge in the center of the propeller core.

  This vortex is dragged by the flow and remains align with the centerline of the propeller, taking the appearance of a braided thread. Its occurrence is less common, as it is a more submerged area of the propeller, and its effects are smaller. See Fig 4.

Fig. 4. Types of vortex cavitation [4].



- ***Laminar cavitation:*** It occurs in propellers with a high angle of attack, which causes that, under certain rotational speeds, the flow has difficulties to "follow the shape" of the blades.

  It remains in a fixed position, being physically separated from the propeller by a thin sheet of fluid, limiting erosion effects on the blades, and having a minor impact on noise, as long as this sheet does not detach from the surface.

- ***Bubble-type cavitation:*** produced by propellers with highly curved blades in the middle section, producing very high localized pressure drops. This type of cavitation produces very strong vibrations and noises, and severely erodes the propeller blades.

- ***Cloud-type cavitation:*** typically caused behind areas of laminar cavitation, and resulting from the detachment of this type. Its appearance is easily recognizable as a mist or cloudy area on the suction face of the propeller.

It produces a high amount of noise and vibrations, in addition to a marked erosion of the blades and rudder.

- ***Blade root cavitation:*** similar to blade tip vortex, but produced at the root. It is less common than the previous ones and is not very damaging, often going unnoticed.

Analysis of the basic equations

As mentioned above, cavitation arises from pressure gradients that occur on the propeller blade faces. Mathematically we can follow the Bernoulli's equation to explain this phenomenon (See eq 1):

$$P_i + \frac{1}{2} \cdot \rho \cdot v_i^2 + \rho \cdot g \cdot h = Cte \qquad (1)$$

Assuming that the height h (depth in this case) is constant, and taking two points, one on the suction face of the blade and one at a considerable distance from the propeller, we can rewrite the equation (see eq 2):

$$P_{suction} + \frac{1}{2} \cdot \rho \cdot v_{suction}^2 = P_0 + \frac{1}{2} \cdot \rho \cdot v_0^2 \rightarrow \qquad (2)$$

$$\boldsymbol{P_{suction} - P_0 = \frac{1}{2} \cdot \rho \cdot (v_0^2 - v_{suction}^2)}$$

Based on this last equation, we can define the local pressure factor as (eq 3):

$$\boldsymbol{C_{pl}} = \frac{P_{suction} - P_0}{\frac{1}{2} \cdot \rho \cdot v_0^2} = \boldsymbol{1 - \left(\frac{v_{suction}}{v_0}\right)^2} \qquad (3)$$

As the flow passes around the profile, it accelerates as a function of its geometry and orientation, producing a decrease in local pressure. The graph in Fig. 5 shows the difference in local pressure coefficients.

If the pressure at the suction face becomes lower than the vapor pressure of the water, cavitation will start to occur.

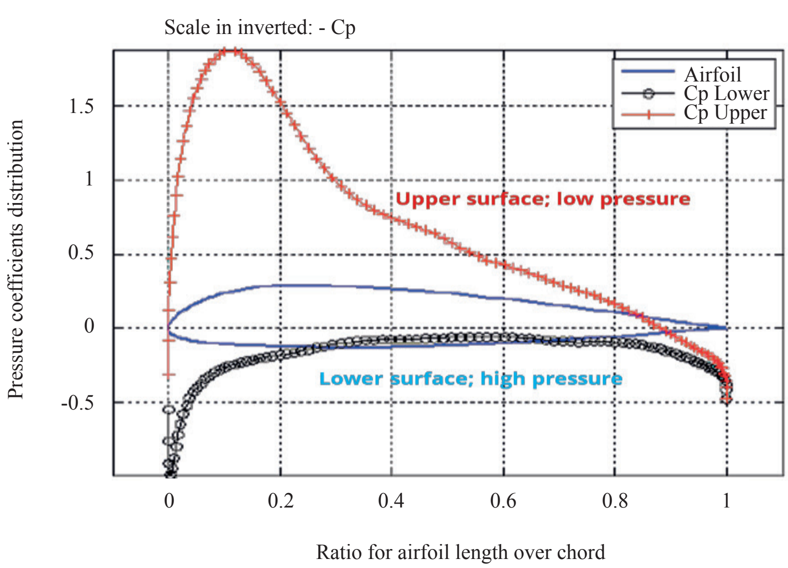
Implications and effects of cavitation

Cavitation, from its earliest stages of appearance until it is fully developed, has many consequences, which vary in severity depending on the degree to which the phenomenon is occurring, and of what type it is.

Mainly the following can be highlighted:

- High losses of propulsive performance caused

Fig. 5. Inverted local pressure in propellers [4].



by the alteration of the normal flow and the pressure gradient.

- Damage of the propeller blades and the rudder: from minor pitting and erosions, to severe damage to the blade surface or edges. If the damage and erosions are too extensive, the propeller blades can even brake, making the propeller unserviceable and inoperable. This can affect the rudder of the ship, with very similar consequences.

- Vibrations: in addition to the physical damage, the bubbles, when imploding, transmit a large amount of noise and vibrations to the hull, impairing comfort on board, and also affecting different components and structures.

- Noise emitted to the environment (URN): similar to the noise and vibrations transmitted to the hull, part of this noise is radiated directly to the marine environment. This has harmful consequences regardless of the type of vessel, being able to highlight:

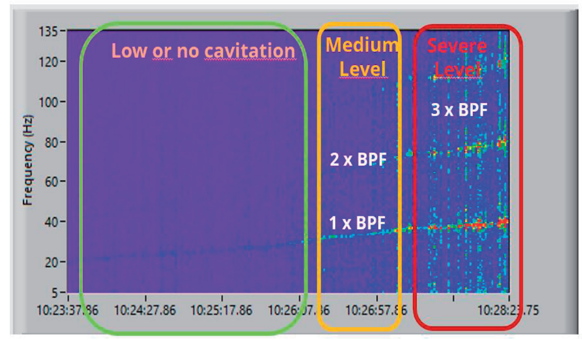
  - In the case of merchant, recreational or civil vessels in general, the noise emitted by ships has a very negative effect on various marine species that mainly use sound to feed or communicate as previously stated, causing the disappearance of individuals of these species in the navigation areas.

  - In the case of military vessels, this noise emitted to the environment makes it possible to detect the vessels that produce it very easily, which could jeopardize the safety of the mission they are carrying out, as well as the ship itself and its crew.

Fig. 6 shows the spectrogram provided by the cavitation system in which the presence of cavitation from low engine revolutions can be appreciated.

It should be taken into account that, in many cases, there is not a single type of cavitation for a given vessel, propeller and conditions, but it can appear sequentially as the propeller speed increases.

Fig. 6. Cavitating ship spectrogram.



Detection methods

Given the impossibility of eliminating this phenomenon, over the years, different methods have been applied to identify and confirm the existence of it on specific existing vessels, all of them being intrusive and/or imprecise.

There are also some formulations that allows the designers to study and predict the behavior of the new ship propellers.

Vessels already built

In the case of working on already built vessels, the options available to tackle the cavitation problem are considerably limited, all of them implying the need to previously observe the phenomenon.

For this purpose, the following intrusive methods of detection and definition of cavitation type are mainly used:

- Temporary windows installed in the hull: Perforations in the hull in which a glass is installed to allow direct observation of the propeller in operation, involving an appreciable modification of the hull, and the intermediation of classification societies.

- Cameras placed external to the hull: Similar to the previous option, but replacing the window in the hull by a camera, which can be installed either on the outside of the hull by means of special supports fixed to it, or inside, in cavities made for it.

Vessels in design phase

In the case of wanting to carry out a cavitation study prior to the construction of the ship, there is more flexibility in order to be able to mitigate this phenomenon to a certain extent.

There are two main methods to predict how cavitation will occur in ships still in the design phase:

- ***Burill's method:*** seeks to minimize cavitation by approaching the problem from the point of view of increasing the area of the blades, and, in consequence, distributing the thrust over a larger area and reducing the pressure gradient produced on its surface typically using the Burill diagrams, such as the one in Table 1.

- ***Keller's method:*** similar to Burill's method, Keller proposes a simplified formulation to determine the ratio of developed area/minimum disk area, based on the characteristics of the propellers and type of vessel and applying a factor named Keller. (Table 1). below shows Keller's formula, together with the K parameter.

Regulations under development

Currently, and within the non-military sphere, work is being actively done on the development of regulations and guidelines aimed at controlling the underwater radiated noise emitted by the ships radiated, focusing on preserving the marine environment and ensuring that maritime transport does not cause irreversible damage to the oceans and its lifeforms.

Three initiatives can be highlighted in this respect:

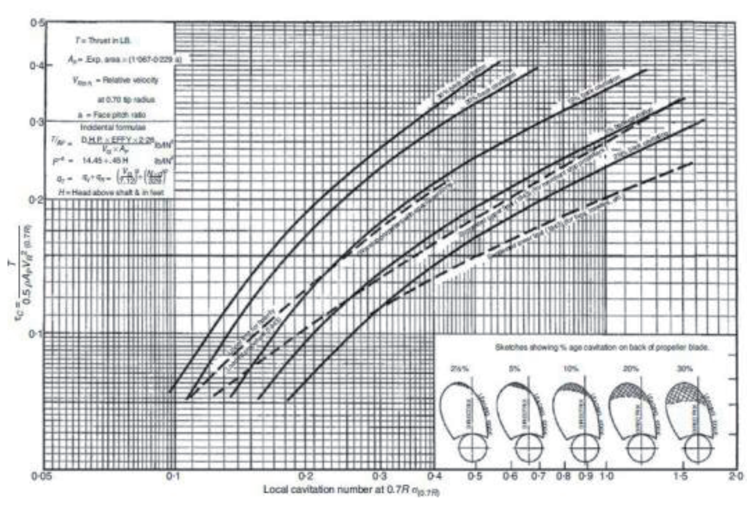
- On behalf of Transport Canada, a working group, the UVNRT, has been formed to establish a series of recommendations and Guidelines aimed at controlling noise radiated into the water in Canadian waters, but which are extrapolable to other shipping areas. Canada is one of the most active countries in these aspects and, for the protection of the killer whale reserve in New Colombia, is giving economic incentives in the port of Vancouver for those ships that have adopted measures to control their acoustic signature.

- The IMO is in the process of updating the URN Guidelines MEPC.1/Circ.833, developed in 2012, tightening the limits that had been set in the previous version, as well as adding new recommendations.

- Added to Transport Canada and IMO, a set of standards is being developed that establishes noise and URN emission limits for merchant ships, depending on their type and

Table 1. Keller formulation and Burill diagram [4].

$$\frac{A_D}{A_0} = \frac{(1.3 + 0.3Z)T}{(P_0 - P_V)D^2} + K$$



characteristics and which will be mandatory: the ISO-3. It is important to highlight the activity of the Spanish flag in these activities.

Both the regulations under development, as well as the Guidelines, take into great consideration the cavitation of the propellers, as they identify this phenomenon as one of the main responsible for the acoustic pollution of the oceans.

NI-CDS System

Motivation and required system characteristics

Given the rapid development that the different regulations are suffering, ships will soon have to comply with strict radiated noise limit levels, in order to adapt to the regulations, and to be able to continue to sail freely in the different zones of the oceans.

In addition, it must be taken into account that the application of advanced and specific design methods for each ship represents very high costs and efforts, which not all shipowners and shipping companies are willing or can afford.

In already built ships, although it is possible to take actions such as the design of new propellers, or the installation of appendages and hull modifications, again, it represents very high costs, in addition to requiring the interruption of the merchant work or missions of the affected ship, resulting in huge losses for the shipping companies.

Another option, applicable to both new and existing vessels, is to delimit the operational conditions in which the vessel can work, seeking to avoid reaching a condition in which cavitation appears, at least when crossing regulated or particularly sensitive areas. However, this implies delays in the works of the vessel, in addition to being complicated by traditional methods to determine when the vessel is cavitating with accuracy.

Consequently, the application of current methods brings with it a series of drawbacks:

- The commonly used methods, in many cases, require the vessel to enter dry dock for installation, with the consequent costs derived from immobilizing the vessel, and the modification itself.

- It is necessary to make physical modifications of relative importance to the hull itself, as well as in some cases to the structure of the ship with its consequent impact on the classification of the ship, safety, etc.

- The methods mentioned above rely on physical and imprecise observation and assessment of the cavitation, which requires the ship to go through as many sailing situations as possible (not only the typical ones). Any case or situation not observed will be an unknown point.

These aspects of the methods currently used have motivated the research and development, by TSI, of a system that meets a series of minimum requirements, which allow an effective and complete evaluation of the occurrence of cavitation phenomena, as well as their intensity, in any propulsor-hull assembly that may be present:

- The system needs to be easy to install and control, so that it doesn´t impact negatively on the availability of the vessel or its performance.

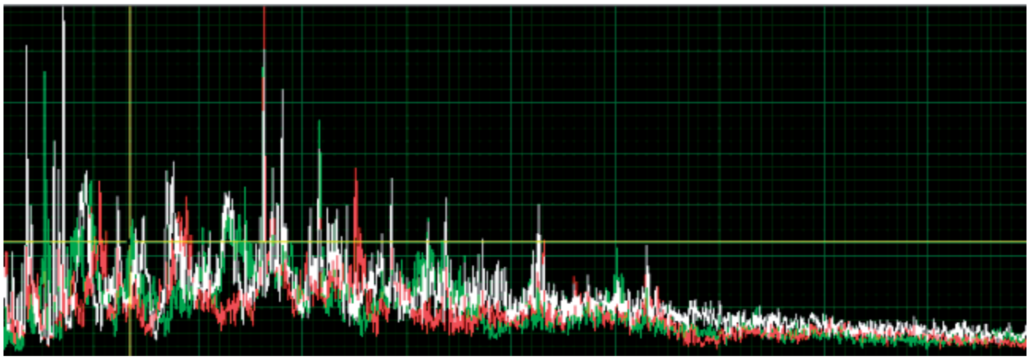
- It is necessary to ensure that its installation doesn´t need deep modifications of the hull or structure for its installation.

- That it is adaptable to each type of vessel, regardless of its size, type or function.

- It must be able to collect and evaluate data from all possible navigation situations, so that it can be known at all times and in every situation, the cavitation state and condition.

Based on these requirements, throughout several projects, a system has been developed, with the capacity of continuously monitoring, in real time, the situation of the propellers during navigation, determining immediately when cavitation starts to occur and with what intensity.

Fig. 7. Frequency broadband spectrums corresponding to cavitation detected in the hull structure.



To achieve this, the system uses one of the most important characteristics of cavitation: the vibrations produced by the implosion of steam bubbles, and transmitted through the ship's hull (structure-borne noise). Fig. 7.

These random excitations, induced by cavitation and transmitted throughout the ship's hull as "structural noise", reach the different spaces of the ship, especially and not exclusively, the spaces located further aft, and are responsible of the vibrations and noise observed in ceilings, panels, glass, etc. of certain compartments. This random structural noise that propagates through the ship's steel is capable of exciting the frequencies of the different elements of the ship's hull, causing these plates to radiate into the surrounding marine environment with the corresponding alteration in the ship's acoustic or "stealthy" signature.

The vibrations or structural noise induced by the cavitation of the propeller are collected, in this case, by means of a series of high precision and sensitivity accelerometers, which are placed in "hard points" of the structure inside the hull. These points should be areas of the structure in direct contact with an element of the hull close to the propeller, or, failing that, they should have a high stiffness to facilitate the transmission of the referred structural noise.

The signals delivered by these accelerometers are collected by the continuous acquisition system and processed by means of a proprietary analysis algorithm, developed and patented by TSI, which gives the following results:

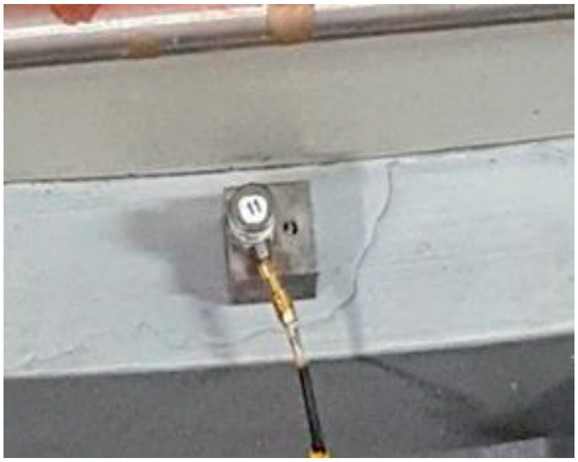
- If the propeller cavitates and with what intensity.
- Under what conditions of draft/load, pitch and speed of the propeller(s) the cavitation occurs. The corresponding history is recorded in the system for further studies.
- The identification of the type of cavitation based on characteristic patterns of induced vibrations is currently under investigation.
- Likewise, the system has been designed to incorporate static parameters such as emissions, consumption, geolocation, etc.

All this is done in real time while the ship is sailing normally, delivering the data continuously to the ship's crew, and allowing them to make reliable decisions at all times based on this information.

The installation of the system, due to its characteristics, also meets the requirement of avoiding long and costly drydocking and major modifications to the ship and its structure, since all parts are installed on the fly and without the need for docking.

- The accelerometers are installed in internal points of the ship's structure, which are studied based on their position and stiffness characteristics, with no need to install anything outside the hull or any modification of it (See Fig 8 and 9).
- The acquisition and processing system is placed in the vicinity of the sensors to avoid long cable lengths and can transmit the information obtained to the bridge and engine control chamber.

Figs. 8 and 9. Accelerometer placed in the ship structure.



Applications

Naval propeller cavitation does not distinguish between ship types, affecting equally (depending on how and what it is designed for) all existing vessels. This makes a system such as the Ni-CDS- Non-intrusive Cavitation Detection System a highly valuable asset for the crew of all ship, regardless of the type and mission of the vessel:

- **Merchant Ships:** The speeds at which these ships usually move are not very high, but the loads to which the propellers are subjected are usually very high, since on the one hand, the propellers of these ships have to move very high amounts of mass, and on the other hand, derived from the need to transport the largest possible amount of goods in the same trip, the shapes of the hull of these ships are not designed with the primary objective of achieving a hydrodynamically efficient behavior.

  Consequently, regardless of whether they are oil tankers, bulk carriers, gas carriers or container ships, among others, the propellers of these vessels can produce cavitation at very low speeds, below 8 knots in many cases.

  The use of a non-intrusive cavitation detection system in these vessels would bring with it a series of very significant advantages, and of great impact for shipowners and ship operators:

  - Reduced propeller, rudder and hull maintenance costs.
  - Reduction of emissions and consumption, avoiding drops in propulsive performance.
  - Future compliance with developing regulations.
  - Greater freedom and ease to avoid navigation restrictions by being able to enter areas with URN requirements, shortening routes and their associated costs.
  - Being able to benefit from economic incentives for port stays, as vessels are equipped with a cavitation control system, as well as for early compliance with regulations.

- **Military Ships:** This is one of the segments most interested in controlling the cavitation phenomenon given the "strategic value" of controlling its stealthiness in certain "silent" operating modes.

  In this case, the vessels are more efficient from a hydrodynamic and drag point of view, which reduces the propeller´s load in their operating conditions, while the propellers themselves are carefully designed to best suit the hulls of their vessels. However, these types of vessels may need to operate at considerably higher speeds than vessels in other sectors, leading to the occurrence of cavitation irremediably.

  Far from impacting "only" on propulsive performance, fuel expenditure, and the noise that affects the various marine species, or the damage to the propellers themselves, in the military case, the aspect of stealth, or in other words, detectability, is of particular importance: Military vessels need in a large number of occasions to go unnoticed and undetected and the lack of knowledge of the exact conditions and moments in which cavitation occurs in the propellers of these vessels causes that, due to the large amount of radiated noise produced by this phenomenon, their stealth capacity is greatly reduced, and they are easy to detect and identify, which poses a risk to the vessel and its crew.

In summary, the main advantages for this type of vessel are:

- Increased knowledge of the navigational condition of the vessel or submarine.
- Being able to maintain a stealth situation in silent operational modes or when required.
- Safety of the crew and the vessel.

- **Recreational Vessels and Cruise Ships:** Vessels in this sector are intended for the enjoyment of their owners. They range from small yachts of small size, to large and luxurious vessels that seek maximum comfort for their occupants.

In the case of small boats, due to the noise produced by the engines and systems themselves, the cavitation phenomenon can go unnoticed, and no advantages can be perceived in the use of a system of the characteristics presented. However, although it is not easily perceived by humans, its impact is present, causing severe damage to the propellers in their operation and reducing their efficiency quickly or even breaking the propeller, which ends up leading, irremediably, in the need to change it.

In the case of larger and luxury vessels, their owners or passengers, the last thing they want to hear is the typical crackling of cavitation on board. If the noise of this phenomenon is perceived, even in the slightest, it could lead to the rejection of the vessel by the buyer or complaints from the passengers, with consequent financial losses for all parties involved.

The fact that the captain has real time information on the state of the propeller in terms of cavitation will allow him to adjust to the sailing conditions to avoid the occurrence of this phenomenon at all times, thus maintaining maximum comfort on board.

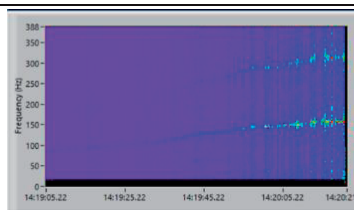
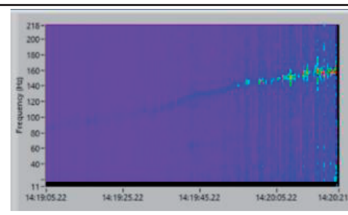
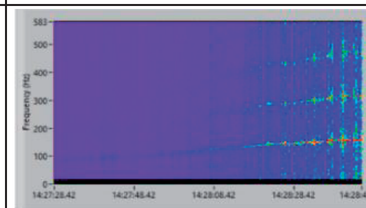
Validation

The first full-scale validation tests of the cavitation detection algorithm were performed within the "On-site Measurements and Assessment" work package lead by TSI, in the framework of the European Project AQUO- Achievement Quiet Oceans, funded by the European Commission. Full-scale vibration measurements were carried out on different types of ships, on the stern structure of the vessels.

Currently, and within the SATURN project framed in the H2020 program, financed by the European Commission, during the experimental tests at full scale on board the ship "Ángeles Alvariño", owned by the IEO- Spanish Institute of Oceanography, another complementary validation of the non-intrusive cavitation detection system was done. The aim is to determine precisely when cavitation occurs and its application to avoid the increase of URN and damage to marine fauna.

Based on the authors experience as noise and vibration consultants in the maritime sector, both nationally and internationally, their professional involvement has been required in certain cases of ships suspected of having cavitation in their propulsion systems. From the recording and processing of the vibration signals in the structure of these vessels by means of the non-intrusive detection system, the presence of cavitation has been verified and confirmed, in some cases, very severe as confirmed by the graphs shown in Table 2.

Table 2. Cavitation indicators obtained by the Ni-CDS.

Note: For confidentiality reasons, none of the vessels shown in the top images corresponds to the spectrograms in the second row.

Finally, it was decided to perform a complementary verification at CEHIPAR in its cavitation tunnel. Fig. 10. shows some of the data obtained from this measurement.

Fig. 10. Verification results of the Ni-CDS.

Conclusions

Based on the preceding points of this article, the following observations stand out:

- Cavitation, as a hydrodynamic phenomenon, has been a problem for the shipbuilding industry for more than 50 years. This phenomenon continues to cause high costs, both directly in the components: propeller, rudder and hull of the ship and its shortened life and maintenance; and indirectly in the propulsive performance of the ship and its emissions of both gases and noise radiated into the water. This has led to the direct involvement of international maritime organizations such as the IMO and the different states, like Canada with initiatives to reduce the noise radiated by ships, to which the Spanish flag has joined, among others. This means that, although it may be difficult for some shipowners to understand this reality, the guidelines under development will end up becoming mandatory regulations.

- In this sense, the authors, as experts in the dynamic-acoustic design of "silent" ships and in the context of their professional activity, have been observing that there are more and more Contractual Specifications in which there is a specific section on control of radiated noise to water, not only for oceanographic vessels, but also for all types of commercial vessels, demonstrated throughout the measurement campaigns in SATUNR, AQUO, or SILENTV, with abundant experimental data showing that the presence of the cavitation phenomenon in the propulsion system of any commercial or military vessel is associated not only with an increase in the entire spectrum of noise radiated into the water at low frequencies of 10 to 1000 Hz, but also with a significant increase in amplitudes (pressure in dB ref. 1 Pa) in the frequency range from 1 kHz to 100 kHz. Wich can interfere with come electronic equipment, like echosounders.

- In the case of military ships and submarines, their non-detectability and, therefore, their "stealthiness" has a strategic value to guarantee the success of their missions, as well as the safety of the ship/submarine and its crew.

- These aspects, together with the economic costs and their impact on the operation of the ship, detailed in this article, make continuous monitoring of ship propeller cavitation essential. The authors, with more than 46 years of experience in vibration and noise control on ships, decided together with the RDI team that, since cavitation cannot be eliminated for certain operating conditions, the only practical and operational solution was the design of a system that would allow its continuous control for different operating conditions.

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Electrical design for efficiency: technical and operational measures for optimizing the use of electrical power on ships

Diseño eléctrico para la eficiencia: medidas técnicas y operacionales para la optimización del uso de la potencia eléctrica en buques

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Abstract

There is currently a growing concern in the shipping industry about energy consumption and environmental impacts. According to the International Maritime Organization's (IMO) energy efficiency guidelines, today's ships must have an energy efficiency management plan to reduce the CO2 emission and other pollutants. In this article, a bibliographic review of methodologies for the optimization of energy consumption on ships is carried out, starting from the identification of sources of energy losses, to the implementation of technical and operational measures that contribute to their improvement, making a qualitative evaluation of the identified methodologies. Sources of energy losses associated with equipment and auxiliary systems are analyzed, as well as opportunities for improvement in the use of electrical energy through the implementation of intelligent energy management systems, high efficiency motors, and lighting. The technical and operational energy efficiency measures described above demonstrate the importance of their implementation from the early stages of the ship's electrical design, as well as monitoring energy consumption during its life cycle, to improve energy efficiency on board.

Key words: Energy efficiency, electrical design in ships, energy consumption, maritime transport.

Resumen

En la actualidad existe una creciente preocupación en el sector del transporte marítimo por el consumo de energía y el impacto ambiental. Según las directrices de eficiencia energética de la Organización Marítima Internacional (OMI), los buques actuales deben disponer de un plan de gestión de eficiencia energética que permita disminuir la emisión de CO2 y otras sustancias contaminantes. En este artículo se realiza una revisión bibliográfica de metodologías para la optimización del consumo energético en buques, partiendo de la identificación de fuentes de pérdidas energéticas y la implementación de medidas técnicas y operativas que contribuyan a su mejora, realizando una evaluación cualitativa de las metodologías identificadas. Se analizan las fuentes de pérdidas de energía asociadas a los equipos y sistemas auxiliares, así como las oportunidades de mejora en el uso de la energía eléctrica mediante la implementación de sistemas inteligentes de gestión de la energía, motores de alta eficiencia e iluminación led. Las medidas técnicas y operativas de eficiencia energética descritas demuestran la importancia de su implementación desde las primeras fases del diseño eléctrico del buque, así como el monitoreo del consumo energético durante su ciclo de vida, con el fin de mejorar la eficiencia energética a bordo.

Palabras claves: Eficiencia energética, diseño eléctrico en buques, optimización consumo energético, tranporte marítimo.

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Introduction

In recent years, the International Maritime Organization (IMO) has implemented several policies to improve energy efficiency in ships and reduce environmental impact during their operation [2]. This paper proposes a methodology based on a literature review. Initially, ship energy efficiency improvement policies issued by IMO are identified. Some causes of electrical system efficiency losses in ships and measures to improve electrical systems are described.

The causes of electrical efficiency losses described are associated with the operation of the Genset engine outside the established parameters, as well as to efficiency losses in the Genset alternator and power transformers due to losses in the windings and in the core. Efficiency improvement measures found in literature include combustion engines with catalytic reduction systems and exhaust gas recirculation, load-dependent transformer efficiency, use of batteries as an additional energy source, implementation of a power management system to avoid overloads in generation, transition of lighting to LED technology, and operation of generators at high capacity

Energy efficiency in ships

Implementing policies, strategies, and technical solutions to reduce greenhouse gas emissions is one of the most significant challenges confronting shipowners and operators in the 21st century [1].
To reduce the negative environmental effects of ships, the International Maritime Organization (IMO) has developed a few tools to monitor emissions. In this context, the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI) are two standardized indicators for energy efficiency assessment. The first one concerns ship design and commissioning, whereas the second one concerns parameter control while a ship is in service [2].

As with other IMO regulations, the flag state of a ship is ultimately responsible for ensuring compliance with EEDI. A verification body issues an International Energy Efficiency Certificate (IEEC) to demonstrate compliance (Maritime Administration or Classification Society). The verification process is divided into two stages. A preliminary verification is performed based on ship design, followed by a final verification test during a sea trial. The shipowner, shipbuilder, and verifier are all involved in the process at every stage of the ship's development [3].

The ship's EEOI is calculated using statistics collected during the voyage and from the ship's operation. These statistics include parameters such as the equipment's fuel consumption, state of the navigation environment, length of the ship's stay in port, and distance traveled [2].

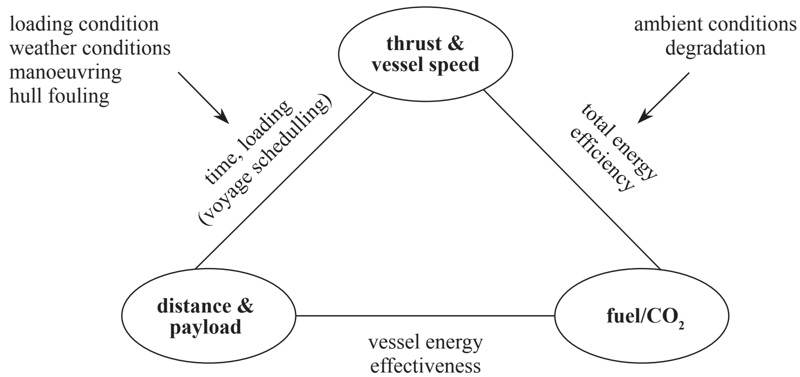
Given the significant changes that ship technologies must undergo, the planned goals are medium-term (by 2030) and long-term (by 2050), with 2008 as the base year. The desired end result is to reduce greenhouse gas emissions from shipping by up to 40% by 2030; 70% in emission intensities; and 50% in total emissions by 2050 [1].

Chemical energy saved in fuels is released as heat through combustion in conventional maritime power systems. The main engines, which are typically diesel engines, convert this heat into work and deliver it to the propellers either directly or via reduction gearboxes. The work is then converted into propulsion thrust by propellers to overcome vessel resistance and accelerate it. Auxiliary diesel engines, on the other hand, convert heat to work, for electrical power, and to power the ship's electrical grid. These power conversions and transmissions improve components, subsystem, and overall system energy efficiency [4]. Fig. 1 shows the relation between vessel energy effectiveness, total energy efficiency and influencing factors.

Sources of losses in the electrical system

A logical first step in discussing how to improve the energy efficiency of a ship's electrical system is to understand the view of power system losses. All elements of an electrical system (transformers,

Fig. 1. Illustration of the relationship between vessel energy effectiveness, total energy efficiency and influencing factors [4].



motors, etc.) provide resistance to current flow and therefore, dissipate some energy to perform their intended function [5].

The losses in power distribution systems can be as follows:

Diesel engine

Diesel engines suffer continuous internal wear during their useful life and under normal operating conditions, resulting in a reduction in efficiency. The loss of pieces is proportional to the hours of operation and can be exacerbated by impurities in the fuel or the presence of particles during combustion. It is possible to recover some engine efficiency by following a motor maintenance plan that adheres to the manufacturer's specifications [6].

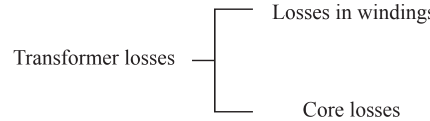
The operation of a Genset outside the nominal conditions established by the diesel engine rating can produce several negative effects. The first one being that the engine may not reach the temperature and pressure necessary to operate properly, causing a black oily fluid to be produced and seep through the exhaust system seals; part of the reason why combustion releases a higher amount of nitrogen oxides into the environment [7]. The second manifests itself when engines are operating at low loads for long periods, causing accumulation of debris in the pistons or cylinders, resulting in loss of power, accelerated wear, and in the worst case, wear of the cylinder liner [7]. Consequently, the motors must be kept operating by the restrictions of their classification so as not to reduce their efficiency and service life.

Transformers

Electrical transformers are static electrical machines that deliver electrical power by changing the voltage level from input to output (primary-secondary). There are currently three types of transformers, depending on their application: power transformers, voltage transformers and current transformers. The last two are normally used to measure or to sample high voltages and currents in circuits that require low values to operate, while power transformers are used to supply loads at the desired voltage.

All three types of transformers are used on ships, however, for the purpose of this paper, only power transformers will be discussed because of their influence on the efficiency of the electrical system. Although transformers are static electrical machines, they present the same losses as rotating electrical machines, except for those related to friction due to the lack of movement of the equipment. Fig. 2 shows the losses according to Chapman [8].

Fig. 2. Transformer losses.



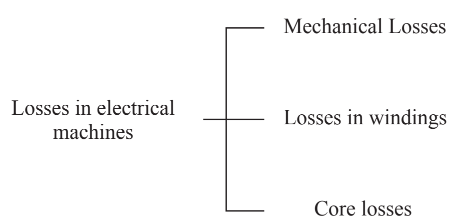
- Core losses: hysteresis, core heating due to eddy currents, vibrations, harmonic current, and voltage components.
- Losses in the windings: power loss due to the resistance of the windings, these losses are transformed into heat.

Alternator

In electrical groups, the alternator is typically a synchronous generator that supplies the required electrical power to the system. The synchronous generator is classified as a rotative electric machine, a category that also includes synchronous motors, inductors, permanent magnet motors, and so on.

Power losses (or efficiency losses) in rotating electrical machines can be broken down into the types of losses in Fig. 3.

Fig. 3. Losses in Electrical Machines.



Source: own elaboration on the base of [8].

Mechanical friction losses are associated with losses due to contact between the bearings and the structures that house them.

Losses in the windings are the result of the energy dissipated by the electrical resistance of the motor windings, including excitation in synchronous generators with this technology.

The losses in the iron core are due to the dispersion of the magnetic field joining the stator and rotor windings as they pass through the fluid, as well as losses in the coupling of the magnetic field in the motor air gap. In addition, losses caused by the eddy currents induced in the iron by the magnetic fields induced by the windings are included.

Measures to improve energy efficiency in the electricity system

High efficiency motors

Combustion engines: Ships designed for global operation must have main engines that meet the strictest Tier III emission standards. The combustion temperature has the greatest impact on harmful substance emissions because an increase in temperature results in more efficient combustion of the air-fuel mixture in the combustion chamber. This is associated with lower particulate matter emissions (primarily soot and hydrocarbons) but an unacceptable increase in nitrogen oxide NOx discharge. The need to solve this conundrum prompted the development of selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) systems [9].

Transformer efficiency as a function of load

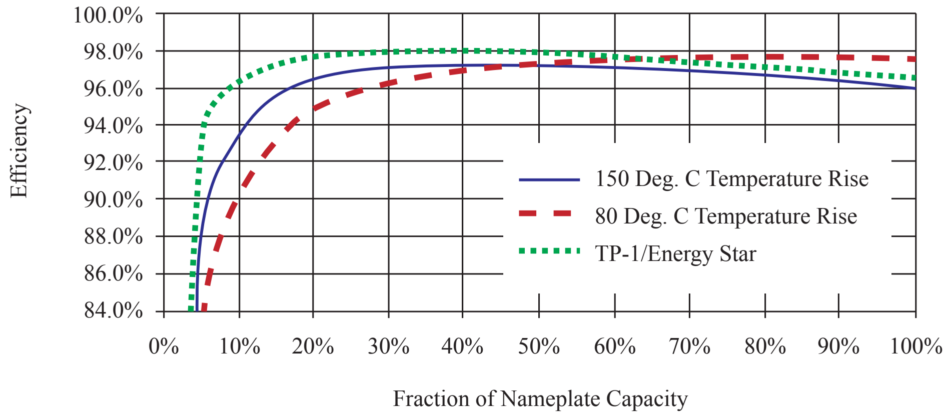
Ships require the transformers be of the dry air-cooled type. Transformer efficiency as a function of load has the behavior presented in Fig. 4 for three types of transformers: for a temperature rise of 150°C, 80°C and TP-1 type transformer with higher efficiency.

It can be noted that the maximum efficiency for all transformers occurs at load percentages between 35% and 60%, depending on the temperature rise. The efficiencies at full load are lower than the maximum transformer efficiencies, which is obtained at partial loads.

Battery compensation

The use of batteries enables an additional source of energy that helps to control the power network, allowing on occasions, one or more engines can be shut down to avoid running at low loads and therefore operating with low efficiency. Consequently, fuel consumption, emissions, and noise-vibration-hardness (NVH) level of the generator engines can be reduced. Other battery functions include peak shaving, regeneration of braking energy and standby power. In the event

Fig. 4. Transformer Efficiency Vs. Load [10].



of high power demand, battery power can help generators sustain high power demands.

Electrical power management system

Electrical generation equipped with an electrical power management system allows controlling the start-up of the service and emergency generators and the electrical power demand to avoid generator overload and blackout [11]. This system protects the generators and prevents their sequential loss using consumer discrimination, and has the following functionalities:

- Automatically reduces the vessel's power demand to keep it within the available generation capacity.
- Sectioning the electrical system, opening the main switchgear busbar disconnector in case of generator failure, to isolate the fault.
- Requesting automatic start and entry into the system of the standby generators.
- The vessel's power demand reduction is performed with the non-vital consumers, according to their classification, by opening the load center disconnectors or disconnecting large consumers at the main switchgear.
- The management system controls the automatic start-up and entry of the emergency generator in case of failure of the primary generation.
- Likewise, the system ensures that the locked-rotor current of the generators is not exceeded by starting electric motors.

Efficient lighting

Over the course of the last few years there has been a massive transition in lighting technology from conventional lighting to LED technology which is more energy and cost efficient. Research [12] suggests that significant energy savings can be achieved by applying LEDs instead of high-pressure sodium or metal halide lamps.

Some of the advantages to be highlighted are:

- Long life: the average lifetime of a LED luminaire is approximately 35,000 to 50,000 hours, therefore, they also generate an economic benefit from low replacement costs and energy consumption.
- Environmentally friendly: LED technology luminaires do not contain toxic chemicals (mercury vapor).
- The initial investment is higher than for incandescent bulbs. However, due to the long lifetime and high energy efficiency of LED bulbs, the investment is quickly amortized.

Energy efficiency potentials of the generator operations

Load sharing practices on ships affect the performance of generators. This can indirectly cause different amounts of fuel consumption, fuel cost, and emissions for the same amount of onboard electrical power generation.

In [13], the energy efficiency of a number of diesel, chemical, ro-ro and barge vessels was evaluated. The annual fuel consumption and cost, and the potential emissions that may occur from possible load sharing applications of the generator sets on the vessel were estimated. Vessel characteristics, generator specification, power demand and time of operation modes were used as input data to assess the potential effects of load sharing practices on generators. The results showed that running the generators at high capacity instead of low capacity could meet the onboard electrical power demand with less fuel. When generators run at 90% of their capacity instead of 40%, the minimum savings in terms of fuel consumption, fuel cost, CO2 and NOx emissions is about 7% [13]. This ratio should be at least 5% in the case of SOx. At the same time, the savings potential for all parameters was about 17%. Generator load sharing practices can be an important operational measure that does not require any investment among the types of energy saving applications for ships [13].

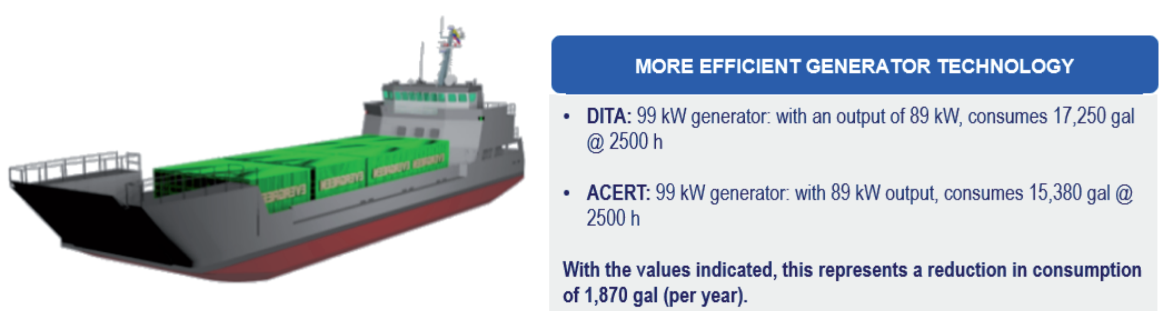
Some technical and operational measures implemented from the electrical design to optimize the use of electrical energy on ships in COTECMAR.

GEDIN-COTECMAR's design and engineering management have implemented systems/ equipment/solutions with new technologies that contribute to energy efficiency in the design phases, and therefore, to lower fuel consumption. Some of the implementations are:

More efficient generator technology

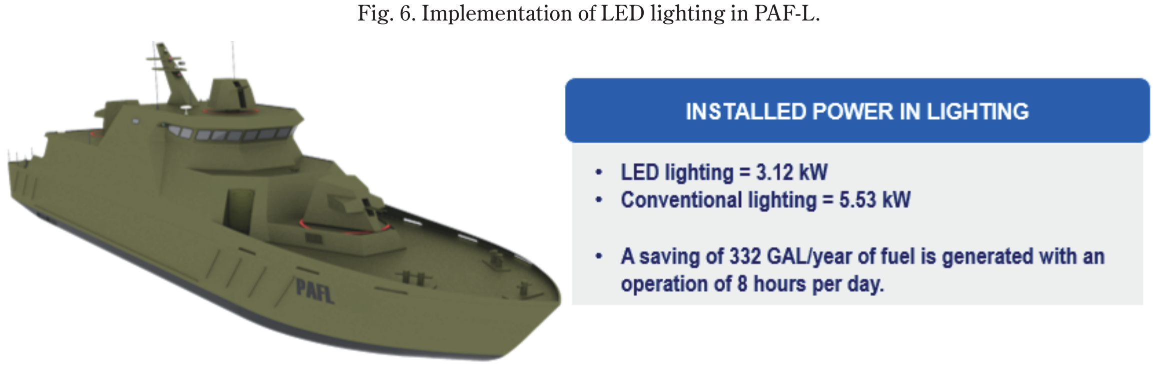
In the BDA (Buque de Desembarco Anfibio) project, generators with more efficient technology were considered to save fuel during the operation periods. Fig. 5 shows the comparison between the DITA Genset technology and the ACERT Genset installed in the BDA.

Fig. 5. ACERT (Advanced Combustion Emission Reduction Technology) Genset in BDA.



Source: own elaboration on the base of [8].

Fig. 6. Implementation of LED lighting in PAF-L.



Source: own elaboration on the base of [8].

Fig. 7. BALCL design with implementation of solar panels.

Source: own elaboration on the base of [8].

Table 1. Applications that have increased efficiency in HVAC systems.

Parameter	Equipment/System	Implementation/Results
Auxiliary systems efficiency	Air conditioning	Evaluation and diagnosis for the energy optimization of the chilled water circulation system: the arrangement of pipes and fittings allows a reduction of the resistance by approx. 40% and an increase of the current pump efficiency by up to 68% (Ref: PAFP-PAFL).
	Hydraulic Systems	Application of Pipe Flow expert, in the design and analysis of hydraulic systems, to determine the diameters, pressures, speeds and routing of pipes to achieve the most efficient operation points of the pump, as well as to determine the pressure loss in the system due to the friction with the flow in the pipes, which contributes to have more efficient auxiliary system arrangements.

Table 2. Implementation of technical and operational measures for energy efficiency on ships.

System	Integration possibility	
	Design Phase	Operational Phase
High efficiency electric motors	x	x
HVAC Optimization	x	
Battery compensation	x	x
Automation and power management systems (PMS).	x	
LED Lighting	x	
Generator operating doctrine		x
Renewable microgrids	x	

LED lighting

In the PAF-L (Patrullera de Apoyo Fluvial Liviana) project, from the design stage, LED lighting was considered to obtain better lighting levels with less power consumption.
Fig. 6 shows the comparison between conventional lighting technology and LED lighting installed in PAF-L.

Renewable microgrids

During the design development of the BALC-L (Buque de Apoyo Logistico y Cabotaje Liviano) vessel, deck 02 was extended to provide an available area for the location of the photovoltaic modules, as shown in Fig. 7. The installed peak power is 1.68kW and per year they can produce 1,903 MWh of energy, which will be used to power the lighting loads on deck 01, contributing to the reduction of fuel consumption which per year would represent 137 gallons and a reduction of 2Ton in the carbon footprint per year.

Efficiency of auxiliary systems

Table 1 shows the considerations taken into account for the optimization of the air conditioning and hydraulic systems, which represent one of the most significant impacts on electricity consumption.

Technology integration

The Table 2 shows the possibilities of integrating technical and operational measures for energy efficiency from the design phase and during the operation of the vessel.

Conclusions

The Colombian shipbuilding industry has undeniably strengthened its capabilities in the design phases to implement technical and operational measures to optimize the use of electrical energy in ships, in alignment with the energy efficiency guidelines of the International Maritime Organization (IMO). From the literature findings, electrical and mechanical losses in motors, transformers, and alternators visibly vary depending on the load and normal operation behavior of these elements. However, the points of view presented on this subject were only from a technical and operational perspective and did not cover considerations on the change of efficiency behavior as a function of time, which is crucial. Therefore, this aspect should be addressed in a subsequent study.

From the design phases, measures have been implemented to improve the use of electrical energy in ships, such as the installation of intelligent energy management systems, use of high-efficiency engines, use of LED lighting, and the optimization of air conditioning and hydraulic systems. However, the challenge is providing comprehensive solutions to support the life cycle in terms of the energy efficiency of ships that require maintenance, repair, or warranty care. Nowadays, it is not enough to design and build a good energy performance of the vessel, but also, to make improvements during the operation phase to contribute to energy efficiency and thus, lower fuel consumption.

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Impacting Factors on the Accuracy of a Fuel Consumption Measurement

Factores que influyen en la precisión de la medición del consumo de combustible

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Abstract

The paper discusses the challenges in performing an accurate fuel consumption measurement and the various factors that affect it. Based on an empirical pressure measurement carried out on a cargo ferry by KRAL engineers, ways to improve measurement accuracy are identified.

Key words: Fuel Consumption, Measurement Accuracy, Influencing Factors.

Resumen

Este documento analiza los desafíos para realizar una medición precisa del consumo de combustible y los diversos factores que la afectan . Sobre la base de una medición de presión empírica realizada en un transbordador de carga por los ingenieros de KRAL, se identifican formas de mejorar la precisión de la medición.

Palabras claves: Consumo de combustible, Precisión de la medición, Factores que influyen.

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Fuel Consumption Measurement and Impacting Factors

The challenge

The accuracy of a fuel consumption measurement depends on many different factors, which result in a number of challenges while performing a measurement.

This white paper explains fuel consumption measurement in the supply and return lines of a fuel consumption device, also known as differential measurement.

In addition to the precision of the individual measuring devices, external influences also affect the accuracy of the measurement result. These include temperature differences between the supply and return lines, fuel pulsations, pipe vibrations and air bubbles in the liquid.

For many fuel consumption devices (engines, generators, boilers, etc.) in industrial and commercial plants operated with diesel or heavy oil, as well as for vehicles (construction machinery, trucks, locomotives, etc.), the fuel is supplied by circulation (Fig. 1).

Fuel consumption is determined using the following formula:

supply flow – return flow = consumption

The difference between the forward and return flowmeters gives the consumption, hence the term differential measurement. The flow rate in the circulation is usually about three to four times higher than the actual consumption itself. This procedure is chosen to ensure a permanent supply of fuel. In addition, the appropriate quality of fuel must be prepared to ensure optimum combustion.

There are flowmeters in both the supply and return lines for measuring the differential.

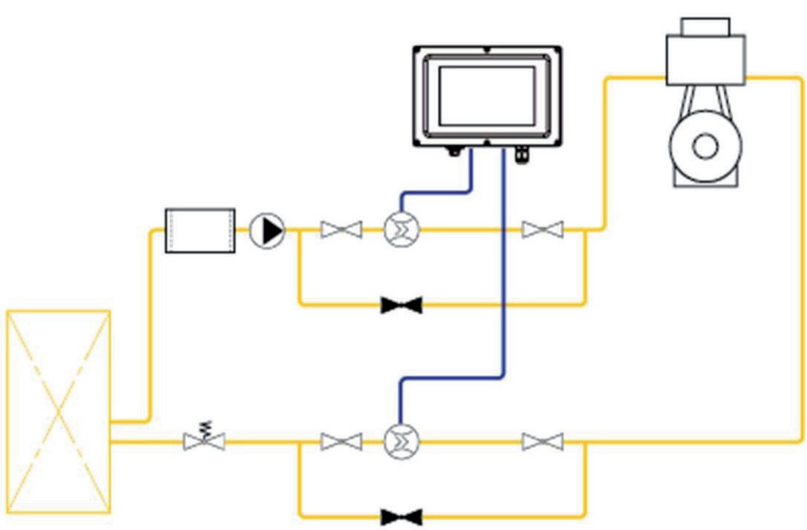
The measuring errors of both measuring devices cannot simply be added together to determine the total measuring error. From a physical point of view, the individual measurement error must be related to the actual consumption value (Fig. 2 and Fig. 3).

Influencing factors

Accuracy of the individual measuring instruments.

Even if other influencing factors have not yet been taken into account, a system error of 2 % can quickly occur with an accuracy of, for example, 0.5 % of the individual measuring devices. The error size depends on the ratio of the flow in the supply

Fig. 1. Wiring diagram differential measurement.



and return lines to consumption. The greater the difference, the greater the error. At full load, accuracy in the system is about 2.5 %, while at low load the measurement error can be up to 10 %.

If, however, measuring devices with an accuracy of, for example, 0.1 % are used for the same flow rates, the total measuring error at full load is significantly reduced to 0.5% or to just under 2 % at low load.

Fig. 2. Calculation of system accuracy (measuring device accuracy 0.5 %).

	flow rate		fm accuracy			
supply line	6000	l/h x	0,50%	=>	30 l/h	
return line	4000	l/h x	0,50%	=>	20 l/h	
					50 l/h	total failure (abs.)
consumption	2000 l/h /					
total failure (abs.)	50 l/h	=>	**2,5%** total failure (rel.)			

	flow rate		fm accuracy			
supply line	6000	l/h x	0,50%	=>	30 l/h	
return line	5400	l/h x	0,50%	=>	27 l/h	
					57 l/h	total failure (abs.)
consumption	600 l/h /					
total failure (abs.)	57 l/h	=>	**9,5%** total failure (rel.)			

Fig. 3. Calculation of system accuracy (measuring device accuracy 0.1 %).

	flow rate		fm accuracy			
supply line	6000	l/h x	0,10%	=>	6 l/h	
return line	4000	l/h x	0,10%	=>	4 l/h	
					10 l/h	total failure (abs.)
consumption	2000 l/h /					
total failure (abs.)	10 l/h	=>	**0,5%** total failure (rel.)			

	flow rate		fm accuracy			
supply line	6000	l/h x	0,10%	=>	6 l/h	
return line	5400	l/h x	0,10%	=>	5,4 l/h	
					11,4 l/h	total failure (abs.)
consumption	600 l/h /					
total failure (abs.)	11,4 l/h	=>	**1,9%** total failure (rel.)			

Temperature difference between flow and return.

Another factor influencing system accuracy is a potential temperature difference of the liquid in the supply and return lines. Especially when measuring the consumption of diesel oil in engines and generators, the temperature in the return line is often higher than in the supply line. The fuel heats up at the consumption device and can be up to 30 °C higher than in the supply line. Since fuel expands when heated, the volume of the liquid changes as a result. In order to avoid additional measurement errors, these temperature and volume differences must be corrected.

The density table (Table 1) clearly shows that a temperature difference of 20 °C for light or heavy oils already produces a density error of about 1.5 %. If the temperature difference is not taken into account, an incorrect density value is assumed for the measurement, which affects the volume value and thus influences the accuracy of the measured value of the individual measuring device. The measurement error caused by the temperature difference is added to the measurement error of the flowmeter. The measuring error of a single measuring point alone has a considerable effect on system accuracy (Fig. 2 and Fig 3).

Example calculation using Fig 3, calculation example with 0.1 % accuracy of the measuring device:

If the liquid is operated at ambient temperature (20 °C) and the consumption device heats it up in the return line to 40 °C, this leads to a ΔT of 20 °C.

According to the density table for fuels (Table 1), the flow rate in this example increases from 4,000 l/h to 4,064 l/h light oil (LFO) in the return line.

$$4{,}000 \text{ l/h x } 1.5 \text{ \%} = 4{,}060 \text{ l/h}.$$

(see Eq. 1: 906.5 kg/m³ at 20 °C / 892.5 kg/m³ at 40 °C LFO).

This reduces consumption from the original 2,000 l/h to 1,940 l/h (6,000 l/h minus 4,060 l/h). The uncorrected consumption value of 1,940 l/h corresponds to an additional measurement error of 3.0 % (2,000 l/h / 1,940 l/h = 60 l/h ≈ 3.0 %).

Pulsations, pressure surges and backflows.

Fuel does not always flow smoothly and evenly through lines and flowmeters. In a complex piping system with pumps, motors and valves, pressure surges and pulsations inevitably occur within the liquid, either temporarily or permanently. Pulsations can occur, for example, when fuel is injected into the combustion chamber of an engine. But even pumps without a uniform pumping capacity or the closing of a valve produce pulsations.

When fuel meets resistance, it compresses. When it expands again, pulsations occur. Such pressure surges cause backflows in the liquid. If these backflows are not taken into account in the flow measurement, an additional measurement error occurs.

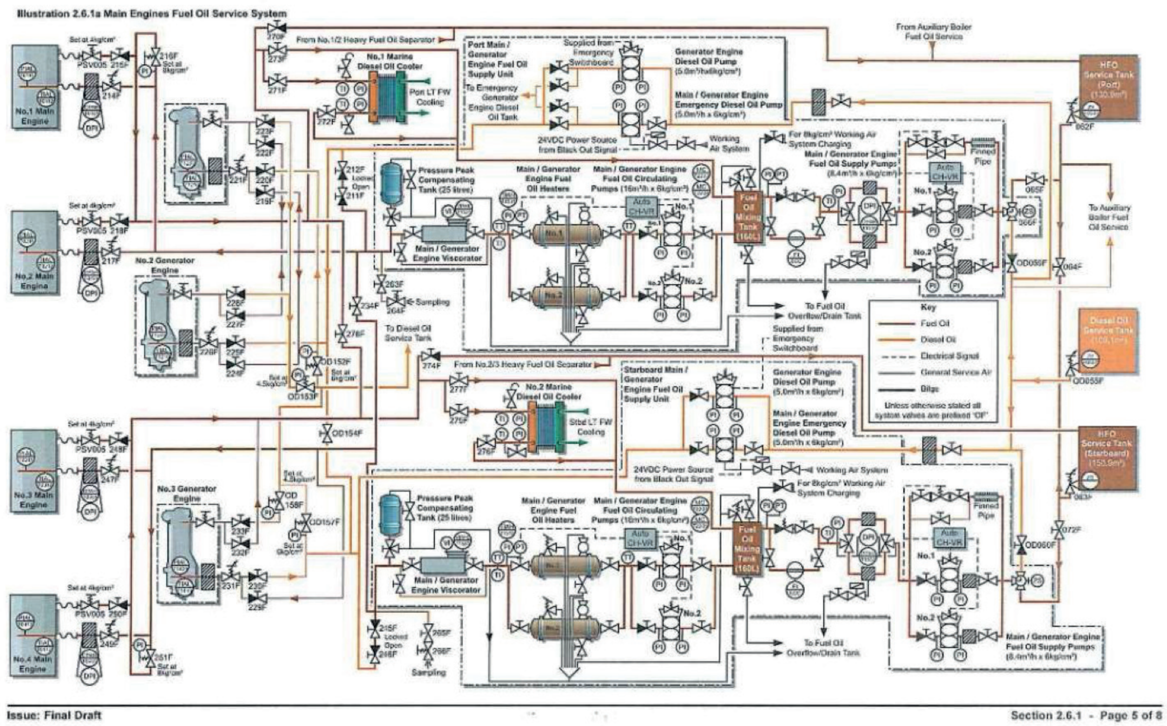
An empirical pressure measurement to determine the pressure peaks and backflows in a fuel line (circulation line with differential measurement) on a freight ferry has shown the following:

The ferry has two independent fuel systems. One is on the starboard side, the other on the port side. Each has two main engines, one system has two generators, the other only one generator (Fig. 4).

Table 1. Density table light fuel oil (LFO) and heavy fuel oil (HFO) (DIN 51757, method B).

T [°C]	ρLFO(T) [kg/m³]	ρHFO(T) [kg/m³]	rel. error LFO [%]	rel. error HFO [%]
20	906.5	976.3	0.0	3.2
40	892.5	961.3	-1.5	1.6
60	878.6	946.2	-3.1	0.0
80	864.4	930.9	-4.6	-1.6
100	850.2	915.6	-6.2	-3.2
120	835.9	900.2	-7.8	-4.9

Fig. 4. P & I - Fuel system diagram.



At a system pressure of 6 to 7 bar, pressure peaks above 12 bar were sometimes measured. These occurred at extremely short intervals (~ 0.5 ms) within a period of 60 to 80 ms and then repeated at cyclic intervals of about 200 to 250 ms.

In this case, six directional changes were detected within the cycle of approx. 60 ms, which could also be quantified volumetrically (Fig. 5: time period between 0.22 s and 0.30 s).

The flow rate here is three times less than 0 l/h, which illustrates and substantiates the backflows in the system. In this example, an error of 12.53 % was calculated on the basis of the backflows generated (Fig 6):

Fig. 5. Measured data for forward flowmeter.

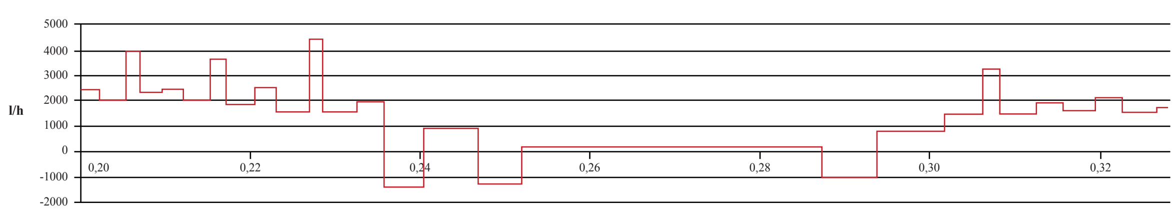


Fig. 6. Evaluation of volumetric measurement data.

Without direction recognition (2x BEG 44)				With direction recognition (4x BEG 44)									
Feed line		Return line		Volume feed line		Volume return line		Total feed line volume		Total return line volume		Volume	
Time	Feed	Time	Feed	Feed	Back	Feed	Back	Feed	Back	Feed	Back	Consumption	
s	ml / flank	s	ml / flank	ml / flank	ml / flank	ml / flank	ml / flank	ml	ml	ml	ml	ml	
0,00802		0,00985		1,762	0,000	1,762	0,000	1555,673	22,903	787,526	0,000	745,243	
0,02204	7,05	0,02902	7,05	1,762	0,000	1,762	0,000						
0,03657	7,05	0,06161	7,05	1,762	0,000	1,762	0,000						
0,04825	7,05	0,11082	7,05	1,762	0,000	1,762	0,000						
0,05735	7,05	0,13746	7,05	1,762	0,000	1,762	0,000	Without direction recognition (2x BEG 44)					
0,0656	7,05	0,15672	7,05	1,762	0,000	1,762	0,000	Total feed line volume		Total return line volume		Consumption	Error
0,07416	7,05	0,17309	7,05	1,762	0,000	1,762	0,000	ml		ml		ml	%
0,08274	7,05	0,18752	7,05	1,762	0,000	1,762	0,000	1620,86		782,24		838,62	12,53

This error value is unusually high and is due, among other things, to the complex piping system with two main motors and three generators. Another cause was a feed pump which, due to wear, was at less than half capacity (according to the type plate). The amount of backflow depends on the design of the fuel system and the components installed in it. Even in a simple system with only one main motor, backflows of up to 5% occur.

Often only very low pulsations occur during initial commissioning with new components. Due to wear and tear of the components installed in the fuel system, the danger of pulsations and thus of backflows increases continuously and can lead to significant false measurements.

Vibrations of the pipelines.

The use of motors, pumps and valves creates vibrations that spread throughout the entire piping system. Vibration-proof sensors in the flowmeter help to avoid measurement errors.

Electronic measuring systems (e.g. Coriolis, ultrasound, etc.), on the other hand, react much more sensitively to vibrations. The measuring principle of the Coriolis is based on an oscillation in the measuring line generated by the measuring device itself. If this oscillation frequency is the same or similar to the vibration frequency of the pipeline, the measurement result is distorted.

In an ultrasonic measuring device, the sound waves from the transmitter to the receiver are deflected by the vibration and thus also influence the measurement result of the consumption device.

Air bubbles in the liquid.

The fuel system is usually a closed system that eliminates air bubbles at an early stage. In some applications, however, air bubbles from the motor get into the return line and thus influence the accuracy of the measurement result. This problem occurs above all with mechanical measuring principles.

Possible Solutions to Improve Measurement Accuracy

In order to achieve the highest possible system accuracy, the best suited measuring principle must be determined. Considering the following parameters can improve the results of the measurement.

Accuracy of the individual flowmeters

The accuracy of the individual flowmeters has a significant influence on the system accuracy and thus the consumption value of the consumption device. In order to minimize overall errors in differential measurement, the accuracy and reproducibility of the measuring devices must be taken into consideration.

Temperature compensation

The example calculation has shown that a temperature compensation is absolutely necessary for a differential measurement without pipe trace heating (which keeps the temperature constant). Even during operation with trace heating, a temperature difference of up to 10 °C between flow and return flow can quickly occur.

Compensation for backflows

Flowmeters must measure both flow directions in order to quantify and compensate for backflows.

Electronic measuring methods (e.g. Coriolis, ultrasound, etc.) are indirect measuring principles. They measure the oscillation of the measuring tube or the speed of sound in the liquid and convert the result into the flow rate. These measuring principles function very reliably under normal application conditions. Due to their inertia, however, they cannot detect or only barely detect pressure surges, as our example shows.

Choice of the right measuring principle

Mechanical measuring methods (so-called displacement meters) record the volume of the liquid directly and largely without delay. The measuring principle must be selected in such a way that vibrations have no influence on the measuring result.

Usage of air separators

Air bubbles can be eliminated with air separators. In addition, the correct positioning of the measuring device must be ensured.

Conclusions

System accuracy when measuring fuel consumption with differential measurement is a challenge because it is influenced by many factors. Some of them are not evident at first glance. If these influences are not taken into account, the measurement error of the system can accumulate up to a value of 20 % and thus lead to incorrect consumption values.

Here, once again, the factors that influence system accuracy in a differential measurement are ranked according to their importance:

- Accuracy of the individual measuring devices.
- Temperature difference in the supply and return pipes.
- Pulsations, pressure surges and backflows.
- Vibrations of the pipelines.
- Air bubbles in the liquid.

If all factors are taken into account, you can rely on the accuracy of the consumption values.

Cybersecurity: a general framework in the maritime and military world

Ciberseguridad: un marco general en el mundo marítimo y militar

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Abstract

In recent decades, the production of information in studies and research papers on the subject of cybersecurity have addressed the convenience of developing cyberdefense capabilities regardless of whether the scope is industrial or military, corporate or State. However, despite the generation of policies to contribute to the synergy of protection, cybersecurity threats continue to grow, affecting all organizations regardless of their size. The article deals with the existing guidelines, policies and environments within the international framework of cybersecurity in the maritime environment and identifies how these are taken through particular measures to the environments of military maritime units.

Key words: Maritime cybersecurity, ships – military vessels, maritime risk management, cybersecurity threats

Resumen

En los últimos años, multitud de trabajos de investigación relacionados con el tema de la ciberseguridad, han demostrado la necesidad de desarrollar capacidades de ciberseguridad y ciberdefensa, con independencia del ámbito de actuación (civil, militar, corporativo, industrial o gubernamental). Sin embargo, y a pesar de la aparición de nuevas políticas para contribuir a la protección de las amenazas de ciberseguridad, estás no han conseguido doblegar el creciente número de amenazas a las que se ven sometidos los sistemas, y que afectan a todas las organizaciones sin importar su tamaño. Por ello, en el presente artículo se analizan los lineamientos, políticas y entornos existentes dentro del marco internacional de la ciberseguridad en el entorno marítimo y se identifican como estas son implementadas, mediante medidas particulares a los entornos de unidades marítimas militares.

Palabras claves: Ciberseguridad marítima, barcos – buques militares, gestión de riesgos marítimos, amenazas de ciberseguridad.

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Introduction

The digital transformation that different sectors have undergone leads to the incorporation of new technological advances and modes of operation in their infrastructures, for the maritime field this includes ships, ports and other facilities [1]. The above, allows cybercriminals to focus their efforts to carry out attacks against companies in the maritime industry, leading experts to consider cyber threats as a major obstacle to the digitalization demanded by the sector [2], at the same time, the digital attack surface is increasing and incidents can have serious consequences for important sectors with an impact at all levels [3].

Although greater interconnectivity between ships, personal devices and onshore infrastructure has improved operational efficiency and physical security, it also increases the risks of cyberattacks [4], making it necessary to focus efforts on the identification of technical issues, legal frameworks, among others, with a maritime impact, without neglecting issues such as blackmail, extortion, and ship hijacking, among others [5]. All this makes it necessary for the different stakeholders to join efforts to prevent and build capabilities to respond to technological incidents.

In the maritime sector, regardless of whether its scope is military or civilian, the integration of radar systems, Automatic Identification System (AIS) and Electronic Chart Display and Information System (ECDIS) through digital technologies, provides several benefits for maritime operations, it also makes ships prone to have greater vulnerabilities on board, increasing the risk to cyberattacks [6].

In addition to the risks identified that are to be mitigated, there are those that are continuously generated as a result of a society where digital interconnection prevails every day, but due to the cultural and work dynamics, preventive procedures are put aside, which makes it more important to have risk management procedures in place in order to identify that personnel management and its technological culture is one of the most predominant aspects to close the vulnerability gap.

This document analyzes the international guidelines and/or policies that have been issued as part of the maritime cybersecurity mitigation measures and the way they have been addressed by the Colombian Navy, with an emphasis on an approach to the security culture and the management of human factors in the existing measures. Based on the above, some general recommendations and lines of work are proposed that seek to strengthen different aspects of this important issue.

Context

In recent years, several studies and researches have characterized cyberspace as a military domain, which is why States seek day by day to build and/or increase their military capabilities through the alignment of policies for the acquisition of resources, allocation of personnel, etc. However, this environment has its own climate, characteristics and questions that necessarily modify the use of techniques that are addressed in traditional warfare scenarios.

Different bodies have taken the initiative to generate guidelines, policies and preventive measures focused on the protection of onboard systems and their entire IT infrastructure, such as the provisions of the International Ship and Port Facility Security Code (ISPS) [7], the International Ship Safety Management Code (ISM Code) [8], the provisions issued by the International Maritime Organization (IMO) on Maritime Cyber Risk Management (MSC-FAL.1/Cir.3) [9] and different recommendations and standards issued by the industry (such as ISO, NIST, etc.) for the mitigation of vulnerabilities and cybercrime.

It is worth noting that maritime security system assessments have focused on identifying risks, but have not taken the critical (and costly) next step of directly addressing the vulnerabilities present specifically in the maritime sector. While such risk assessments are important, it is still in the process of detailing safety issues in the systems that control ships and their ports of call [10].

Guidelines

Studies developed in recent years indicate that there are prudent measures that individuals, organizations and nations can implement to improve their cybersecurity. These best practices lead us to the four areas vulnerable to cyber incursions: Software, Hardware, Policies and People [11].

The programs and equipment are the most addressed from the technical area, which is why policies and people are developed in greater detail.

Policies and People

Main International Organizations:

OAS - Organization of American States

Its origin dates back to the First American International Conference, held in Washington, D.C., from October 1889 to April 1890 [12].

The regional efforts of the OAS-led Cybersecurity Program are multifaceted and focus on three axes, as summarized at Table 1:

Table 1. OAS Cybersecurity Program. Taken: [13]

Cybersecurity Program		
I	II	III
Policy development:	Capacity building:	Research and awareness raising:
The Program assists OAS member states in developing national cybersecurity strategies that involve all relevant stakeholders and are tailored to each nation's legislative, cultural, economic, and structural situation of each Member State.	The Program helps to establish national computer security incident response teams (CSIRTs) and provides tailored technical assistance and training opportunities. Additionally, it has the CSIRTAmericas network, which provides intelligence on cyber threats and trends in the region.	The Program develops technical documents, toolkits, and reports to guide policymakers, CSIRTs, infrastructure operators, private organizations, and civil society by highlighting current developments and identifying key cybersecurity issues and challenges in the region.

NATO

The purpose of the North Atlantic Treaty Organization - NATO is to guarantee the freedom and security of its members through political and military means.

Although there has been an increased awareness on maritime cybersecurity in the industry, the results of several surveys show that there is still room for improvement from the technological and organizational point of view [14], which has driven NATO to direct the field of cybersecurity and adopt the guidelines indicated in Table 2, which directly impact the military field.

The achievement of adequate security policies and measures is useless unless they come hand in hand

Table 2. NATO policy on cyber defense. With information: [15]

NATO policy on cyber defense			
Developing the NATO cyber defense capability	Increasing NATO cyber defense capacity	Cooperating with partners	Cooperating with industry
NATO's Computer Incident Response Capability (NCIRC) protects NATO's own networks by providing centralized, round-the-clock cyber defense support.	NATO continues to improve the state of its cyber defense through education, training and exercises. NATO conducts regular exercises, such as the annual Cyber Coalition Exercise, and is also enhancing its capabilities for education and training.	Engagement with partner countries and other international organizations to improve shared security by identifying common approaches. NATO works with, among others, the European Union (EU), the United Nations (UN) and the Organization for Security and Cooperation in Europe (OSCE).	The private sector is a key player in cyberspace. Information sharing, exercises, training and education are just a few examples of areas where NATO and industry are working together.

with the achievement of a cybersecurity culture based on awareness raising, teaching and learning; the entire cyber risk environment is framed in initiatives of different organizations such as NATO and the UN that are segregated to organizations in the maritime field for its application from the civil and military sector.

IMO: International Maritime Organization

The United Nations Organization, based in the United Kingdom, is responsible for the safety and security of navigation and the prevention of pollution at sea.

It is the global authority responsible for setting standards for safety, security and environmental performance to be observed in international shipping. Its main function is to establish a regulatory framework for the maritime transport sector (80% of the world's shipping industry moves by sea) that is fair and effective, and that is adopted and applied internationally [16].

As part of the strategies, it issued the Guidelines on Maritime Cyber Risk Management in 2017 to strengthen cyber security in consideration of the digitization of ships. As part of these guidelines, the IMO recommended that each flag state integrate and manage cyber risk issues in the vessel's safety management system (SMS) in accordance with the International Safety Management Code (ISM Code) [17], issued Circular MSC-FAL.1/Circ.3 Guidelines on the effective management of maritime cyber risks [9], and Resolution MSC.428 Management of maritime cyber risks in safety management systems [18].

TMSA: Oil Companies International Marine Forum

Another organization that has reacted to these changes and quickly updated its guidelines to the new circumstances is the OCIMF (Oil Companies International Marine Forum), a voluntary association of companies involved in the maritime transportation of crude oil, oil and gas, whose mission is to be the leading authority on the safe and environmentally responsible operation of oil tankers, terminals and offshore support vessels; its TMSA (Tanker Management and Self Assessment) program provides such companies with means to improve and measure their SMS, including in it cybersecurity aspects and requirements applicable to these sectors [19], which include the following:

1. Patch and software management procedures.
2. Processes and guidelines for the identification and mitigation of cyber threats.
3. Password management procedures.
4. Development of a cybersecurity awareness and training plan for all personnel involved.

IMCA: International Maritime Contractors Association

IMCA (International Maritime Contractors Association) represents the majority of contractors and production chains associated with the offshore maritime construction industry and its main objective is to help organizations prioritize defense against today's most common and damaging attacks on IT infrastructures [20].

It has also updated its recommendations on cyber threats, which are included in its Security Measures and Emergency Response Guidance - IMCA SEL 037/M 226 [21], consisting of 20 controls and sub-controls focused on various technical measures and activities. The following are included:

- Active management of device inventory and authorized and unauthorized software.
- Bastioning of end devices and network devices.
- Assessment of the team's cybersecurity skills and training program.
- Penetration testing to assess the strength of an organization's defenses.

National Navy of Colombia

The National Navy of Colombia, in order to secure the information that is stored, processed and transmitted in the different computer assets and data centers, issued the information security policies, framed in its Permanent Directive 2014-18 [22], which defines and establishes the mechanisms for measuring information risk, the roles and responsibilities at each level of the generation and custody of information, which measures must be implemented to secure the information and the media in which it is stored and processed, and the means for the transmission of this information between data centers and terminal stations.

Similarly, and for the proper implementation of the directive, the Digital Security Manual [23] has been established, which defines the guidelines and procedures for the implementation of the security directive of the units of the Navy of Colombia; therefore, the units of the naval fleet must implement all the necessary measures for the assurance of the information and systems used for processing, among others; this manual covers, inter alia, aspects such as:

- Assessment and treatment of information security risks.
- Asset management.
- Physical and environmental security: Measures to prevent unauthorized access to facilities,
- information generation, processing and transmission equipment, protection against external and environmental threats.
- Safety of operations: Defines system and asset protection measures, information backup copies, systems and operational software assurance, among others.
- Management of information security incidents: establish criteria for treatment, registration of the incident and handling, update of risks and their management.

Fig. 1 shows the main information assets on which the protection mechanisms related to the policy are established [22], the same assets that are found in all naval units and must be protected in accordance with the information security guidelines, thus protecting the systems from possible attacks on the information or the systems used for its generation, processing and/or transmission, attacks that will not only put the information at risk, but also the integrity of the ships and their crews.

The maritime sector needs a clear identification and understanding of the threats to which it is exposed, especially in the transport and tourism sector, since the military sector, due to its own operational conception, has implemented complementary methodological strategies for risk management.

Fig. 1. Information assets. Source [23].

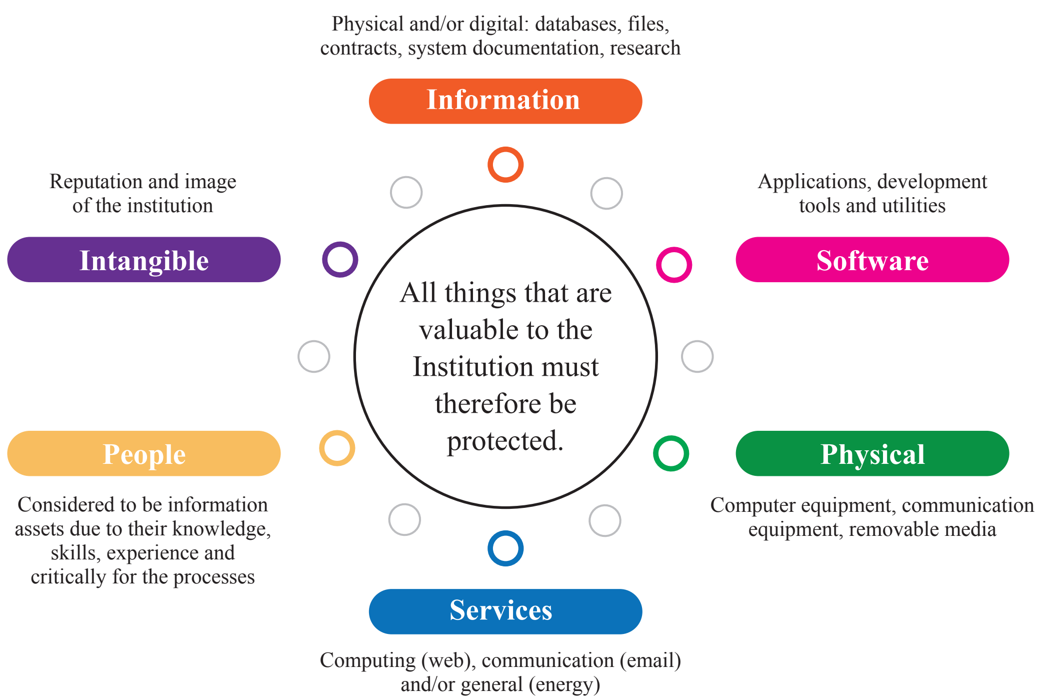


Table 3. Main existing security framework(s) for addressing cybersecurity in the maritime industry

	NIST	ISO	MITRE	COBIT	BSI IT-Grundschutz	OWASP	ENISA
ORIGIN	United States Government	International Organization for Standardization	Mitre Corporation	Information Systems Audit and Control Association: ISACA	Federal Office of Information Security	OWASP Foundation Non-profit organization	European Union Agency for Cyber-Security
OBJECT	A set of guidelines used to minimize organizational cybersecurity risks.	Details specific security controls, internal policies and standardized protocols that are recommended to protect data from misuse or theft	To represent adversary tactics used in a security attack. Documents procedures, techniques and tactics that can be used for advanced persistent threats.	To research, develop, publish and promote an authoritative, up-to-date international set of generally accepted information technology control objectives for day-to-day use.	To provide practice-oriented minimum standards and recommendations for action in the area of computer and web security.	OWASP is a computer security community that works to create articles, methodologies, documentation, tools and technologies that are released and can be used free of charge by anyone.	To improve information security in the European Union. To contribute to the development of an information security culture for the benefit of citizens, consumers, businesses and public sector organizations in the European Union.
METHOD	Identify, protect, detect, respond and recover	Plan, do, check and act	Use of tactics, techniques and procedures on a common basis	Planning and organizing, acquire and implement, deliver and support, evaluate and monitor	Methods, Instructions, Recommendations and Aids - Self-help.	Open and collaborative code.	Development of guidelines, best practices, risk analysis and assessment, and awareness.
USER	Individual companies and other organizations	Companies and organizations	Industrial environments	Governments and businesses.	Companies and organizations	Companies, educational organizations and individuals	European Union States and private sector
PURPOSE	The NIST Framework categories are focused on optimizing risk management and improving the security of systems and assets. They evaluate the actions and policies that are compared with the planning, objectives and resources for continuous improvement.	This family of ISO 27000 standards seeks to guide an organization in the implementation of an Information Security Management System (ISMS) using the ISO 27001 standard together with others. E.G. IEC 61162-460, ISO 16425:2013, IEC 62443-4-1:2018, etc.	Structured list as a way to describe and classify the known trends of attackers orderly recording in matrices the tactics and techniques used providing a taxonomy of the actions that are carried out both on the offensive and defensive side in cybersecurity aspects.	Defines the components for creating and sustaining a governance system: processes, organizational structures, policies and procedures, information flows, culture and behaviors, skills and infrastructure, elements known in the model as Catalysts.	This methodology for information security management systems (ISMS) encompasses technical, organizational, infrastructure and personnel aspects in equal measure. It provides a systematic approach to information security that is compatible with ISO.	One of the fundamental principles of OWASP is that all of its materials are freely available and easily accessible on its website, making it possible for anyone to improve the security of their own web applications. The materials offered include documentation, tools, videos and forums. Perhaps its best-known project is the OWASP Top 10.	To provide support and resources to the member states and the institutions of the European Union in relation to cybersecurity. This includes sharing best practices, promoting collaboration among stakeholders, and providing technical assistance in the development of cybersecurity policies and strategies.
CERTIFIES	No	Yes	Yes	Yes	Yes	Partial/ Courses	No
REFERENCE	[24], [25]	[26]	[27]	[28], [29]	[30]	[31]	[3]

Cybersecurity frameworks play a key role in providing structured and detailed guidance for the protection of critical systems, risk management and incident response. These frameworks enable maritime organizations to build robust cybersecurity capabilities, identify vulnerabilities and implement appropriate controls to mitigate associated risks. In addition, by following internationally recognized frameworks, maritime organizations can establish common and standardized practices, which facilitates collaboration and sharing of threat information in the sector seeking to foster resilience processes in an increasingly challenging environment. Table 3 presents a summary of some of the existing cybersecurity frameworks that, from an industrial point of view, have been applied in the maritime field to encourage their implementation in risk management.

Policy Consolidation

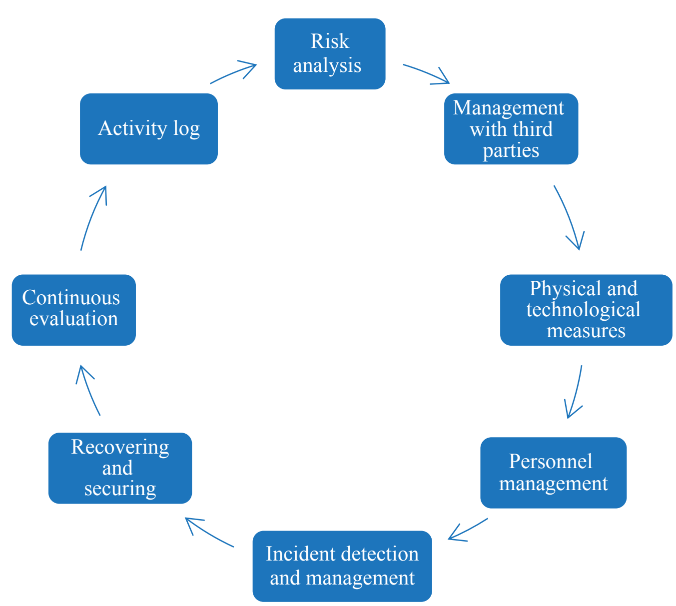
Maritime operators, from an industrial and commercial point of view, are required from January 2021 to comply with a series of security requirements and obligations, and must approve security policies for networks and information systems based on the principles of comprehensive security, risk management, prevention, response and recovery, lines of defense, periodic reassessment and segregation of duties [32]. Military vessels, due to their own operational nature, adopt some of the recommendations and integrate them as part of the technological threat mitigation process by carrying out some of the recommended activities, highlighting the cycle proposed in Fig. 2.

Conclusions

The main conclusions of this article are presented below:

- Cybersecurity is a race between attackers and defenders, where the advantage goes to the attacker, because they can choose the attack methodology and have the time to choose the best way to do it. Since we cannot be completely sure, we must take all the knowledge that we can add between the events that have occurred and the technological analysis of our organization.
- The exponential use of data for analysis and decision making, smart ships, the "industrial internet of things" IIoT, among other factors, is increasing the amount of information available for organizational use as well

Fig. 2. Basic aspects to fulfil. Source: own design



as for cyberattackers. Although there are working frameworks, official references and technological tools, cyber risk management in the maritime field still lacks working spaces from the organizational, technological and user spheres for maritime cybersecurity to become an inherent part of ships at all levels, ranging from onshore managers to ship personnel, led by their captain and those tasked with cyberthreat technology.

- The continuous technological evolution means that all the measures taken for the mitigation of risks aboard ships are constantly evaluated, according to the policies and reports that are permanently generated by the different stakeholders involved in the operation and maintenance of systems, but this must go hand in hand with adaptation, depending on the application environment.

Future Work

In order to continue developing the proposed issues and master the subject, the following future works are proposed:

- To identify possible existing gaps in frameworks, standards, guidelines, rules, etc. in order to propose an initial viable solution for the vessels built in and that are part of COTECMAR.
- To support the construction of a framework to characterize, measure and take actions to mitigate vulnerabilities using knowledge bases, expert input, etc. as backbone.
- Based on the items described above, to propose a case study to conduct a review of: 1. Cybersecurity practices currently applied and 2. Cybersecurity practices generated from the proposal.

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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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