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# EU-CargoXpress: wind propulsion concept

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## Abstract

The EU-CargoXpress project suggests the usage of sustainable energies to reduce the fuel consumption. The updated concept consists of hoisting the superstructure and using it as a sail together with the conventional propulsion. This paper presents the study of the sail performance by means of a computational analysis and wind tunnel tests. Moreover, a research of the energy saving in different operational areas has been conducted. It is concluded that there is a significant energy saving by using the superstructure as a sail which leads to a reduction of fossil fuel consumption and consequently, a reduction of greenhouse gas emissions.

*Keywords:* sail; aerodynamics; computational fluid dynamics; wind tunnel; fuel consumption;

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## 1. Introduction

Nowadays the 90% of all the global trade is transported by sea and the shipping industry highly depends on fuel. Since there is a finite amount of fuel, the cost is continuously increasing and it is not likely to change in the future. Furthermore, the problem is not only the fuel cost but the environmental concern. Every day the governmental air and water quality regulations become stricter.

These reasons have led the shipping industry to make vessels cleaner and more economical by optimizing their engines and hulls. The objective is reducing fuel consumption, or reducing emissions, which is normally simultaneous. But, the potential to enhance the existing propulsion systems is almost

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exhausted. Consequently, new technologies are needed, especially using renewable energies combined with conventional propulsion systems.

The aim of EU-CargoXpress project is to develop a new generation of competitive cargo-vessels for accelerated maritime and fluvial shipping using innovative concepts and technologies; in order to support the greening of surface transport and prepare for fast and efficient modal shift in ports. One of the considerations of this project is to use sustainable energies, such as the solar energy or wind energy, to reduce fuel consumption for some transport scenarios. In this paper, the wind-contribution research is presented.

## 2. State of the art

In this section the existing technologies which use the wind as a source of power are presented: sails on masts, Flettner rotors, turbosails, kites and structural wings.

**Sails on masts**. Sails on masts include both traditional sails and wings, which are airfoil-like structures that are similar to airplane wings. In the late 1970s, the high oil price stimulated the interest in wind power for merchant vessels. Some interesting vessels were built or converted like the “Shin Aitoku Maru” tanker and the “Usuki Pioneer” bulk carrier (O’Rourke 2006). Currently, the Solar Sailor Company has patented SolarSails which harness renewable solar and wind energy simultaneously. Moreover, the 305m long cruise vessel “Eoseas” has been designed to carry six sails with a total surface of 12440m$^2$.

**Flettner rotor**. This technology uses the Magnus force to propel a vessel. This rotor is a cylinder rotating around its own axis and exposed to an airflow moving at right angles to that axis. The cylinder experiences a lateral force that acts at right angles to the airflow and the axis of rotation. In 1924, Anton Flettner rebuilt the sailing ship “*Buckau*”. It was equipped with two rotors but the system was less efficient than conventional engines. But recently, ENERCON Company has built a 130 meters long vessel with four Flettner rotors (ENERCON 2010). It is estimated that the vessel can reduce fuel cost by 30%.

**Turbosails**. In the 80s Captain Jacques Cousteau and his colleagues designed and prototyped the first wind-propulsion cylinder based on the Savonius principle, the Turbosail System. In 1986, they patented the idea named “Apparatus for producing a force when in a moving fluid”. A turbosail is a fixed, hollow, rotating metal cylinder that works like an airplane wing. The cylinder is perforated with thousand of little holes to allow the air to enter and escape. Fans, moved by engines, are placed at the top of the turbosail to accelerate the flow around the wing-masts and increase the lift, producing the driving force forward. A ship called Alcyone was build and equipped with two 10m high turbosails. Two diesel engines provided the necessary power to complement the wind.

**Kites**. At least two firms have developed kite-assisted systems for application to commercial cargo ships: the German company SkySails (SkySails n.d.) and the American KiteShip (KiteShip n.d.). In 2006, it was announced that Beluga Shipping had purchased a SkySails kite system to be installed on the newly built 140-meter heavy cargo freighter MS Beluga SkySails. It is estimated that using kites, the fuel costs can be lowered between 10-35% depending on the wind conditions.

**Structural wing**. This innovative concept is developed on the EU-CargoXpress project (Rosenkranz n.d.).

## 3. EU-CargoXpress project

This is a collaborative Project of the Seventh Framework Program called “Greening of surface transport through an innovative and competitive CARGO-VESSEL Concept connecting marine and fluvial intermodal ports”, or the acronym “EU-CargoXpress”. It is an ongoing project during the redaction of this paper. The conclusions of the project are expected to be drawn throughout 2012.

The project concentrates on those subjects which have the mayor impact on future sustainable and green marine transport, investigating alternative energy forms, usage and conversion, best low resistance hull forms, materials to lower the lightweight of the vessel and innovative cargo loading and port accessing devices making this concept very competitive to the ever growing road transport. The planned competitive cargo-vessel includes highly innovative features not yet used by the marine community.

In the following, the specifications of the cargo-vessel currently available are presented. These values are likely to be slightly modified by the end of the project. Summary of the initial project characteristics:

- Type: Cargo-Vessel type
- HSC-code, coastal transport for feeder
- Main dimensions: Length 83m, beam 21m, draught 4.68 m
- Displacement: 3000mt
- Capacity: 200 TEU
- Deadweight: 2000 t
- Speed: 13kn
- Catamaran with sail-wing and crane

The concept of a structural wing is one of the pillars of the EU-CargoXpress project. It is an innovative concept to use part of the superstructure as a sail/wing. The project studies the possibility of designing the cover of the holds as a sail. Moreover, the cover/superstructure could also be the crane for loading and unloading containers. That is, if the wind is appropriate, the wing is hoisted and used to propel the vessel. If there is no wind or it is not adequate, the wing is lowered to cover the hatches. If the vessel is in-port, the wing becomes the crane.

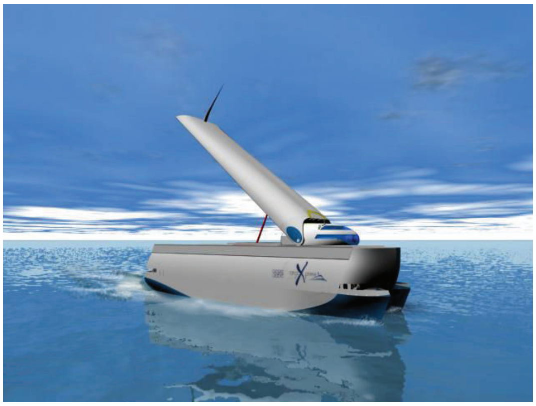

Fig. 1. EU-CargoXpress project

In this paper, the study conducted at the Universidad Politécnica de Madrid is presented. It is focused on the aerodynamic contribution of the structural sail. It is assumed that whatever the loads applied on the sail, the catamaran has the sufficient stability and structural strength.

## 4. Sail performance

Three different shapes of the superstructure have been studied and they contribution to the propulsion have been quantified. First a numerical analysis has been conducted using computational fluid dynamic (CFD) software. Then, a model of the most effective shape have been modeled and tested in a wind tunnel (WT) to validate the results obtained from the software.

### *4.1. Simulations*

The numerical analysis has been carried out using the computational fluid dynamic software CD-Adapco's STAR-CCM+ 5.04.006 (CD-Adapco 2010), which is a Reynolds Averaged Navier Stokes Equations based solver. The calculations of this study have been run at an Intel® Core™ i7-920 Processor with a Linux 2.6.32-27 kernel. A typical simulation has required around 50 hours for a 4.5 million element mesh.

The physical models utilized as in (Izaguirre-Alza et al. 2010) in these simulations are: three dimensional, stationary, gas (air), constant density, turbulent, SST k-omega, segregated flow model, implicit unsteady and all y+ wall treatment. The most suitable boundary conditions, necessaries to reproduce the real behavior of the sail have been set: no-slip wall (sail, bridge), slip walls (deck, sides, sky), velocity inlet (inflow) and zero pressure outlet (outflow). The true wind is the airflow produced in the atmosphere due to natural causes whereas the apparent wind is the true wind minus the boat speed. The apparent wind is the airflow experimented by somebody (or the rigging) when the vessel sails. Therefore, at the inlet, the apparent wind is specified.

The x-axis is the centerline (positive to the bow), the z-axis is the vertical direction (positive upwards) and the y-axis is the transversal direction (positive to port. The origin of the reference system is the center of the axis around which the sail is hoisted. The reference system is fixed to the sail and the wind is introduced with different angles. In order to obtain the thrust and the power provided by the sail the appropriate geometrical transformations are conducted.

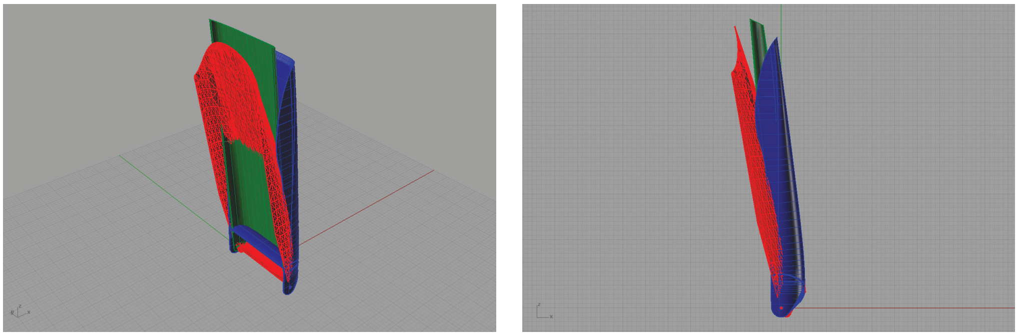

Fig. 2. (a) Perspective view; (b) side view of the first geometry (red), second geometry (blue) and third geometry (green)

It has been assumed that the sail will be hoisted with wave heights lower than 4 meters which correspond to true wind speeds of 30 knots. Taken into account the studied operation areas (see section 5), this sea condition occurs the 90% of the time. These true wind speeds lead to apparent wind speeds (AWS) which range from 1 knot to 40 knots approximately. The apparent wind angle introduced ranges from 0º (from the stern) to 80º (starboard). If the apparent wind angle (AWA) is greater than 80º the sail rotates until the relative apparent wind angle becomes again 80º. Therefore, the sail performance is studied only up to 80º. According to the cargo-vessel specifications, the sail rotates 60º to each side.

### *4.2. Geometries*

Three geometries of the structural sail have simulated. The first geometry has a rounded shape and curved edges. The second geometry is flat with two ailerons, one on each side. The third geometry is even flatter and it has smooth rounded edges. This last geometry has the most slender shape among the three of them as it can be observed in figure 2. The forces and moments calculated with the CFD are referred to these shapes.

### *4.3. Comparison*

Forces are calculated at different apparent wind angles (AWA). Since the dimensions of the shapes are different, in order to compare the sail performance, it is a common practice to calculate dimensionless coefficients. For example, the force coefficient is defined as equation (1) where “F” is the force obtained using the CFD (in N), “ρ” is air density (in kg/m³), “S” is sail total area (in m²) and “AWS” is the apparent wind speed which has been set at the inlet (in m/s).

$$CF = \frac{F}{0.5 \times \rho \times S \times AWS^2}$$

In figure 3, the longitudinal force coefficient and the side force coefficient are plotted. From 0º to 80º the results presented are obtained directly from the forces of the CFD. From 80º to 140º, the value at 80º is transformed geometrically assuming that the sail rotates up to 60º, as mentioned before.

The most important contribution to the thrust comes from the positive longitudinal force. Therefore a high positive value of CX is desirable. On the other hand, the side force contributes negatively to thrust and moreover it decreases the stability. Consequently, small and negative values of CY are better. The figure of CZ is not included since the values are small and constant regardless of the apparent wind angles, as it was expected.

As it can be seen in figure 3a), the curve of the first geometry has a great decreasing slope. Moreover, after 90º of apparent wind angle, the sails contribute negatively and generate resistance instead of thrust. The third geometry also decays but in a less pronounced way and its longitudinal force coefficient curve is the highest one which indicates that this shape is the most efficient one.

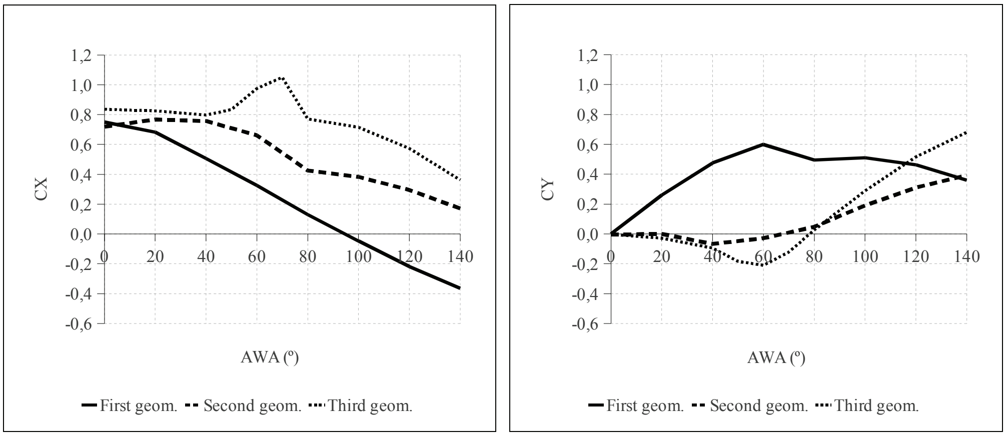

Fig. 3. (a) Longitudinal force coefficient; (b) Side force coefficient

In figure 3b) the side force coefficient is plotted. The first geometry produces the vessel sail down leeward in the whole range whereas the second and the third, permits the vessel sail up windward for low apparent wind angles. Approximately, from 80º on, these sails also generate a force down leeward. At low apparent wind angles the third geometry is very efficient whereas at high apparent wind angles, the second geometry is slightly better. According to the figures 3a) and 3b), the second and third geometries are the most effective ones.

Now, the power that could be saved at a constant vessel speed is calculated for both shapes. The value of forces is obtained from the CFD, then, the thrust is calculated. If a constant vessel speed ($VS$) is assumed, the power ($P_{saved}$) is obtained by simply multiplying the thrust and this speed. Throughout the study it has been assumed that the vessel speed is constant regardless of the wind contribution. The goal of using the sail is the reduction of fuel consumption and no increasing the vessel speed.

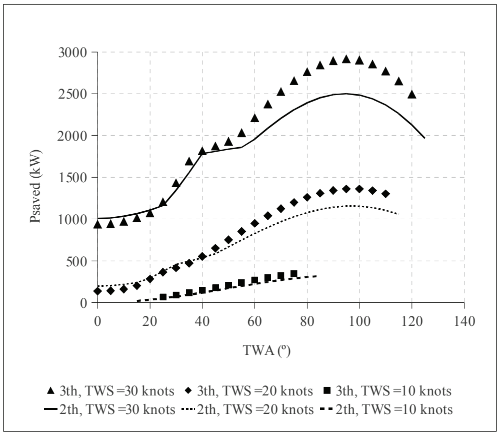

Fig. 4. Saved power at 15 knots of vessel speed provided by the second and third geometries

In figure 4 the values of $P_{saved}$ are presented for the second and third geometries at different true wind speeds (TWS) and true wind angles (TWA). In this case, constant 15 knots of vessel speed have been assumed. With these figures it can be easily evaluate the potential of the sails in different scenarios. For example, with the third geometry, if the mean true wind is 20knots at a certain operation area it can be expected a thrust between 200kW and 1400kW depending on the wind direction and the sailing course. Figure 4 shows that for strong winds and the appropriate combination of sailing course/wind direction, the sail could provide almost 3000kW.

### *4.4. Validation*

According to the discussion of the previous section a model of the third shape has been built and the CFD data has been validated with wind tunnel (WT) tests. These have been conducted at the IDR/UPM (Instituto Universitario de Microgravedad “Ignacio Da Riva”). This is an Institute of the Universidad Politécnica de Madrid (UPM) for R&D activities in the field of space science, microgravity and engineering. The wind tunnel that has been used is the A9. It is an open return and closed test section wind tunnel. This section is 3m long, 1.8m high and 1.5m wide.

Forces and moments have been measured for different apparent wind angles and the CFD conditions have been reproduced. As well as in the previous analysis, the forces have been transformed into dimensionless coefficients. In figure 5 the longitudinal force and side force coefficients obtained with the wind tunnel data are plotted together with the CFD data. As it can be seen, the results are promising. The most important coefficient is the CX since it represents the largest force value. The worst difference between the CFD and wind tunnel data occurs at 60º of apparent wind angle and it is under 20%. It is clear that the CFD curves capture the tendency even the peak at 70º. In the side force coefficient case the curves differ. Since the contribution of the side force to the thrust is considerable less than the longitudinal force, the fact of being slightly different do not imply considerable variations when comparing the power provided as it is proven in next section.

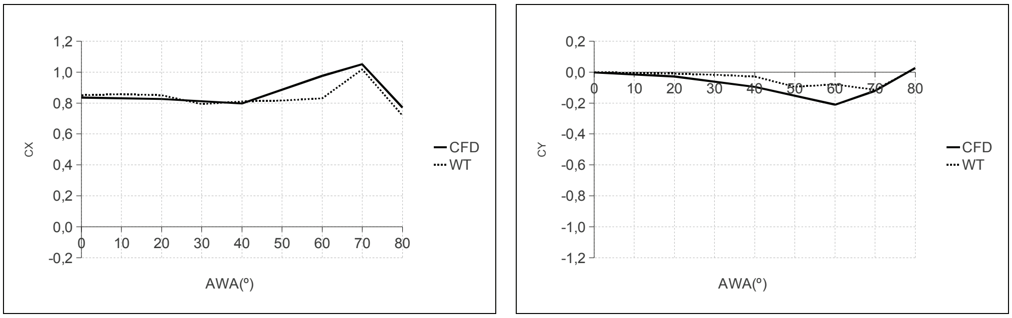

Fig. 5. (a) Longitudinal force coefficient; (b) Side force coefficient

## 5. Real scenario

It has been proven that the structural sail can provide a large value of power at a certain combination of wind intensity and angle. But now a real scenario must be introduced in which the most common wind intensities and their probability of occurrence are taken into account. Six routes have been chosen along which this cargo-vessel could navigate. The routes have been provided by the partner of the project in charge of the operational issues.

### 5.1. Wind characteristics

In order to characterize the wind at different routes, the intensity, direction and probability are required. One of the most complete database used in the maritime field is the Global Wave Statistics (GWS) (BMT 1986). The information given is related to waves but there is a correlation between those wave heights and the wind speed at 10 meters above sea level. The seas and oceans are divided in different areas. Each area is also divided into 8 directions of wind and into 4 seasons in a year. The GWS provides the probability in each area, in each season, and in each direction of having certain wind intensity.

### 5.2. Probability

The saved power that it is obtained from the sail has been called $P_{saved}$ at it is calculated directly from the CFD data or WT data. But, if the question is “during a year, which is the average power that it is expected to be obtained at a certain route?”, the relevant power is the “$P_{sail}$”. In this power the concept of probability is included:

$$P_{sail} = \frac{P_{saved} \times \Pr ob_{wind}}{\Pr ob_{sail}} \tag{2}$$

where $P_{saved}$ is the power saved which is calculated from the thrust obtained using the CFD data or the WT tests for different vessel speeds, wind speed and angle. $Prob_{wind}$ is the probability of having a certain wind speed and angle. Finally, $Prob_{sail}$ is the total probability of using the sail which depends not only on the intensity (limit of 30knots of true wind speed) but apparent wind angle (values over 140º are not affordable since the sail only rotates 60º). This power gives the annual average saved power when the sail is up taken into account the wind occurrence.

### 5.3. Results

The methodology to study the viability of using the structural sail combined with conventional systems has been presented. First, the sail performance is analyzed with a CFD, or wind tunnel tests, to obtain the aerodynamic forces (*FX, FY, FZ*). After the appropriate geometrical transformation the thrust is obtained. Then, a constant vessel speed (*VS*) is assumed to calculate the saved power ($P_{saved}$). Then, the navigation route is set to obtain the course and the wind intensity/direction probability. Finally, the expected power ($P_{sail}$) is obtained as well as the probability of using the sail ($Prob_{sail}$).

In table 1 the values of the annual average expected power and the probability of using the sail, calculated with the CFD data, are presented. As it was expected the higher the vessel speed, the lower the probability of using the sail and higher the obtained power. The results indicate that in average, half of the time during a year the sail could be hoisted. It is also concluded that the route at which the sail is more interesting is the Lobito-Banana route.

Table 1. Third geometry, sail power obtained with CFD data

| | VS = 15 knots | | VS = 13 knots | | VS = 10 knots | | VS = 5 knots | |
|---|---|---|---|---|---|---|---|---|
| Routes | $P_{sail}$(kW) | Prob$_{sail}$(%) | $P_{sail}$(kW) | Prob$_{sail}$(%) | $P_{sail}$(kW) | Prob$_{sail}$(%) | $P_{sail}$(kW) | Prob$_{sail}$(%) |
| Kiel – Riga | 750 | 42 | 658 | 45 | 511 | 52 | 260 | 61 |
| Aberdeen – Dunkerque | 897 | 41 | 787 | 44 | 622 | 49 | 319 | 57 |
| A Coruña – Bourdeaux | 974 | 42 | 872 | 46 | 697 | 48 | 381 | 52 |
| Marseille – Cartagena | 761 | 40 | 655 | 42 | 511 | 46 | 285 | 51 |
| Alexandria – Tripoli | 722 | 39 | 635 | 42 | 612 | 47 | 268 | 60 |
| Lobito – Banana | 1025 | 50 | 902 | 50 | 723 | 51 | 404 | 52 |

In table 2, the results obtained with wind tunnel data and CFD data are compared at 13 knots of vessel speed. It can be seen that the CFD results overestimate the expected power. At this vessel speed, which is the design speed, the difference between the two sources of data is below 10%. As mentioned before, the longitudinal force has been simulated correctly and this is the force component which contributes the most.

The goal of this study is the demonstration of the reduction of fuel consumption by using the superstructure as a sail. It has been already measured the capability of the sail to provide a certain amount of power. Now, this power must be compared to the power necessary to compensate the hydrodynamic resistance at a certain constant speed. This is the effective power (EHP).

In figure 6 the effective power and the expected power (*$P_{sail}$*) are plotted. The effective power curve has been obtained from the towing tank tests of the first hull in study. Throughout the project different hull forms have been developed in order to minimize the hydrodynamic resistance. Therefore, it is expected that the values for the last geometry in study would be lower than the values presented in this paper. The values of the expected aerodynamic power are the average of the six routes at each vessel speed.

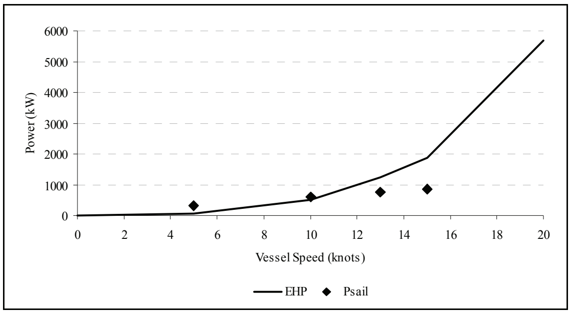

Fig. 6. Effective power (*EHP*) compare to the expected power (*$P_{sai}$*))

It is observed that at 13knots the 40% of the power required to propel the vessel could be obtained from the sail. The average probability of using the sail at that speed is 45%. This is, the 45% of the time during a year instead of consuming fossil fuel to generate 1240kW of effective power, only 488kW would be required to keep 13knots of constant speed. At vessel speeds below 10knots, the vessel could be propelled by the sail.

Table 2. Third geometry, comparison between CFD and WT results (13 knots of vessel speed)

| | Kiel – Riga | Aberdeen – Dunkerque | A Coruña – Bourdeaux | A Coruña – Bourdeaux | Marseille – Cartagena | Alexandria – Tripoli |
|---|---|---|---|---|---|---|
| CFD, $P_{sail}$(kW) | 658 | 787 | 872 | 655 | 635 | 902 |
| WT, $P_{sail}$(kW) | 603 | 721 | 802 | 599 | 583 | 824 |

## 6. Conclusions

Through the analysis of the results and the comments indicated in the previous paragraphs, the following conclusions can be drawn:

- The aerodynamic performance of a structural sail has been simulated with the computational fluid dynamic software CD-Adapco's STAR-CCM+.
- The results obtained with the computational software have been validated with wind tunnel tests. The comparison of the results is promising.
- The power that can be obtained from the sail has been calculated taken into account the probability of wind occurrence at six different navigation routes.
- The expected power obtained from the sail has been compared to the effective power required to compensate the hydrodynamic resistance. It is concluded that there is a real chance to reduce the fossil fuel consumption by using the sail.

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