Viability study of sailing propulsion combined with a conventional system

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ABSTRACT/RESUMEN

For many years now, sails have been used as a propulsion system. At present, they are restricted to recreational/sport crafts since the appearance of the first steam vessels in the beginning of the 19th century. But in the last years, due to the increase of fuel price and the pollution of the environment, it is being studied the possibility to introduce again the sail as a propulsive method combined with other conventional systems.

In this paper, it is studied the viability of using a sail as a propellant with other conventional systems of propulsion. First, a state of the art of the existing technologies is included. After considering the concept of apparent wind, the range of use of this complementary propulsion is presented. The calculation methodology, the numerical simulations and the wind inputs from a specific route are also included.

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. Everyday the governmental air and water quality regulations become stricter.

This leads 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 exhausted. Consequently, new technologies are needed, especially using renewable energies.

In the past, global trade was powered by wind but after the arrival of steam power and later, diesel engines, sailing cargo vessels were relegated to the history books. Nowadays, due to the price of fuel and pollution, there is a new revival of wind power. The shipping industry has high requirements on propulsion technologies using offshore wind which is: an endless energy source, free of charge, powerful at seas and renewable.

Since the 80s, there has been a new attempt to bring back commercial sailing vessel. But there are some drawbacks that have not yet been totally overcame such as: the cost of the equipment, the inability to schedule wind power, the structural reinforcement, the size of the sailing equipment, among others.

Various methods have been developed to fulfill the requirements but unfortunately no system has been able to come up to the expectations on a global scale yet. Nevertheless, due to the current high fuel cost, there are now feasible solutions. It is foreseeable that, as long as the energy supply problem continues rising, wind will be destined to be the future propulsion power.

Despite the goodness of this type of renewable energy, it is clear that the wind power is intermittent and commercial vessels cannot exclusively depend on it since there are routes and schedules to keep. Therefore, there will be a conventional propulsion system in parallel with the sailing equipment.

In this article it is presented a methodology to develop a viability study of a sailing propulsion system combined with a conventional system. The study will be applied to a structural sail as stated below.

The remainder of this paper is organized into seven sections. In section 2, the existing technologies are described. In section 3, the apparent wind concept is introduced. In section 4, the methodology is summarized. In sections 5, 6 and 7, the three steps of the methodology are explained in turn and they are applied to a real scenario. Finally, in section 8, conclusions are drawn.

2.- Existing technologies

In this section the existing technologies which use the wind as the source of power are presented. Not only the technology is described but projects in which they have been applied are included. Moreover, the advantages and disadvantages are explained.

2.1.- Sails on mast

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. It was calculated an average fuel reduction of 30%-40% but due to the falling oil prices at that time, the projects were canceled [1]. In Denmark, the "*Windship"* bulk carrier was designed with six masts with fixed sails. Energy savings of up to 27 % were estimated, but the system was never tested because there were many disadvantages.

The cruise vessel "*Eoseas"* has been designed at the Yards STX [2]. On its 305 meters of length there are six sails with a total surface of 12440m². It is calculated that the new technologies applied in this vessel will allow reducing the 50% energetic consumptions. The designers estimate that the Eoseas would cost around 30% more than a conventional cruise vessel but its developers are confident that the investment will be amortized by the reduction of fuel consumption. This boat is still in a project stage.

Figure 1: Eoseas Project

The Solar Sailor Company has patented SolarSails which harness renewable solar and wind energy. These sails have been installed at the "*Solar Albatross*". This is the first commercial hybrid vessel propelled by fossil fuel, stored electricity, wind power and solar power, in which this technology has been tested. This vessel is a 24m long, 100 passenger carrying catamaran ferry, with stow-able SolarSails. According to the company, in early trials when sailing at 15 knot of true wind intensity and 45 degrees of true wind angle from the bow, the boat speed increased almost 2knots for the same engine power.

Figure 2: Solar Albatros

The use of sails on masts can reduce the fuel consumption and therefore, reduce the emissions too, but there are certain potential disadvantages:

- The rig takes up valuable loading space and there can be restrictions during loading/unloading since the cranes must work around the rigging.
- Mast creates drag in unfavorable winds. Furthermore, safety risk exists for

the crew due to the inflexibility of the system with regard to changing wind conditions. Especially in squalls, masts and sails can cause ships to heel dangerously.

- When navigating with sails, the vessel tends to heel. This would be unfeasible for container and bulk cargo vessels to operate under the typical inclined position of sailing ships. In order to avoid this situation excessive ballast is needed which is uneconomical.

However, the large-scale return of wind power using sails is unimaginable, due to the expected increase of fuel cost in next years.

2.2.- Flettner Rotor

The Flettner Rotor 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. The effectiveness of the Flettner Rotor was first demonstrated in 1928.

In 1924, Anton Flettner rebuilt the sailing ship "*Buckau*" (see figure 3). It was equipped with two cylinders, each 18.3 meters high and 2.8 meters in diameter, to propel the ship. The two cylinders where put in rotation by individual motors. The rebuilt ship could sail into the wind at 20-30 degrees, while the vessel with its original sail rig could not tack closer than 45 degrees to the wind. However, the rotor system was less efficient than conventional engines. The gain in wind power was not enough to compensate for the energy needed to drive the rotors and therefore, the cylinders were dismantled.

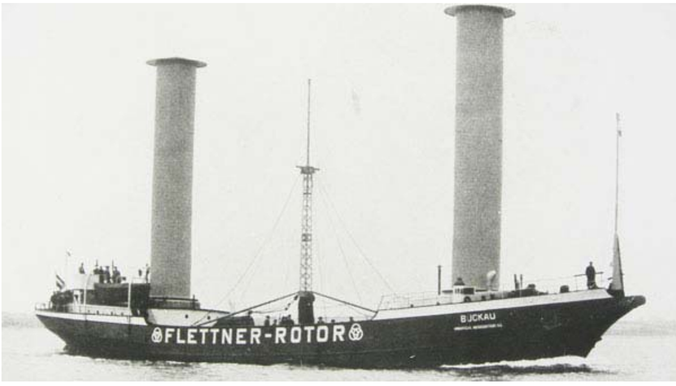

Figure 3: Buckau

Flettner's invention did not succeed in his lifetime but nowadays the Flettner rotor is again being tested as a parallel propulsion system. Currently, Enercon Company has built a 130 meters long vessel with four Flettner rotors for its transport of wind turbine equipment [3]. The vessel called E-Ship 1 (see figure 4) uses wind energy to reduce fuel costs and emissions. E-Ship 1 uses four giant 25 meter high, 4 meter in diameter, rotating, vertical Fettner rotors positioned two fore and two aft to harness wind energy. It is estimated that the vessel can reduce fuel cost by 30%.


Figure 4: E-Ship 1

2.3.- Turbosail

In the 80s Capitain Jacques Cousteau, Professor Lucien Malavard and Dr. Bertrand Charrier, developed another wind traction system. They 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", patent number US 4630997(A).

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 (see figure 5). Two diesel engines provided the necessary power to complement the wind.

Figure 5: Alycione

The design of the turbosails on-board has some drawbacks such as: the large loading space it takes, it is still not efficient enough and it still expensive comparing to other technologies.

2.4.- Kites

At least two firms have developed kite-assisted systems for application to commercial cargo ships: the German company SkySails [4] and the American KiteShip [5]. The main characteristics of these kites are the following:

- The kites fly at 100-300 meters above the free surface of the sea which permits the kites generate 25 times the amount of energy of conventional sails due to the high speed winds at that height.
- Comparing to other wind traction devices, kites do not require a mast and can be easily stowed. This means that they need little space on board and

do not disturb the loading/unloading operations.

- They could be fitted to almost any existing cargo vessels.
- It has low investment costs comparing to other systems but higher efficiency of energy savings.
- These devices incorporate an automatic control system resulting in easy handling and high reliability.
- Unlike conventional wind propulsion systems, kites cause small heel angles and therefore, there is no need for ballast.

It is estimated that using kites the fuel costs can be lowered between 10-35% depending on the wind conditions. It is concluded that the environmental and financial benefits can be compelling. Kite suppliers indicate that by using this system, ship operation will become more profitable, safer and independent of declining oil reserves.

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. The vessel was launched the 17th of December 2007 (see figure 6).

Figure 6: Beluga-SkySails

In February 2011, Cargill Company signed an agreement with SkySails to install a 320m^2 kite on a vessel of 30,000 deadweight tonnes, making it the largest vessel propelled by a kite in the world. Cargill and SkySails aim to have the system fully operational in the first quarter of 2012.

As well as the previous systems, kites have also potential disadvantage. The kite cannot be operated on courses against the wind. That is because the force is created by the wind being captured in the sail area and pulling the ship; for this reason, the system cannot be used when the apparent wind is forward of the beam.

The greatest drawback of kites is that they cannot be operated at low winds. Some studies reveal that the potential hazard of the kite falling in the water, particularly in the ship's path, outweighs any financial benefits obtained from this system. Moreover, the kite should not be operated in areas with dense ship traffic for safety reasons. In these areas the vessel might need to rapidly change her course, or stop, and it is difficult to do so when the kite is flying.

2.5.- Structural wing

The EU-CargoXpress project [6] is currently investigating a promising concept of a patented container vessel with on-board loading equipment and very low fuel consumption, as well as an structural sail. It is in study the possibility of designing the cover of the hatches as a sail. Moreover, the cover/superstructure could also be the crane for loading and unloading the containers.

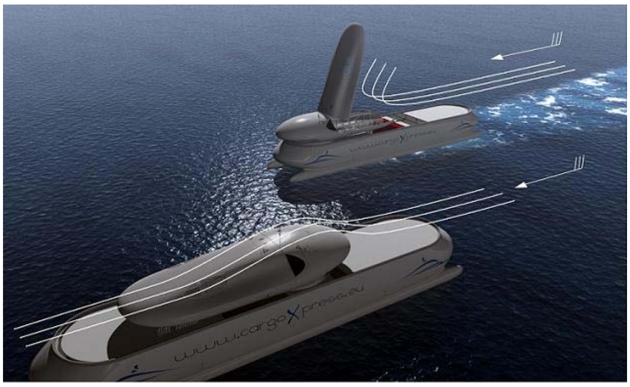

Figure 7: EU-CargoXpress project

According to the project, the catamaran type vessel, of medium to high speed, will be suitable to access small maritime or fluvial ports to freight cargo serve as a feeder to the larger maritime terminals. It will be 85m long approximately with a 1600t of displacement. It is estimated that a great amount of fuel could be saved by hoisting the superstructure as a sail (see figure 7). The conclusions of the project will be drawn in 2012.

This is the type of sail that is analyzed in this paper. It is assumed the shape of a sail and the viability study will be applied to a fictitious cargo vessel which uses the sail as an auxiliary propulsion system and also, as a cover of the holds. The vessel is a 96m long catamaran with a deck height of 21m. The sail structure has a 75m of span and 5375m² of sail area. This is not a real vessel but an example designed with the information obtained from the database of the CEHINAV Research group. Moreover, a feasible navigation route will be analyzed from the North-West of Spain to the South-West of France.

3.- Apparent wind

This is an important concept in the paper: the difference between the true wind (TW) and the apparent wind (AW). 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 (BS) (see figure 8).

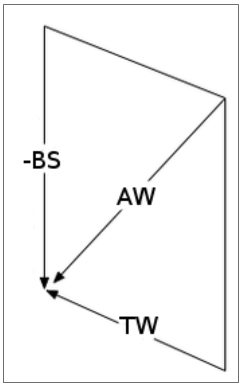

Figure 8: Boat speed, true wind and apparent wind

That is, the apparent wind is the airflow experimented by somebody on-board (or the rigging) when the vessel navigates. This is the wind that propels a sailing boat if the contribution is positive or it increases the air resistance if the contribution is negative. The sign of the contribution depends on the angle of attack between the apparent wind direction and the sail. It is usually considered that the contribution to the propulsion is positive, if the apparent wind angle is in the range of 0º to 140º from the stern and to each side, for a high performance sail. This range depends on the geometry of the sail. Therefore, the difference between the true wind and the apparent wind is the boat speed.

Obtaining the intensity of the apparent wind depending on the true wind speed and the boat speed is a simple geometric problem. The resulting equation is:

$$AWS = \sqrt{\left(TWS \cdot \cos\left(TWA\right) - BS\right)^2 + \left(TWS \cdot \sin\left(TWA\right)\right)^2} \qquad \textit{Equation 1}$$

where AWS is the apparent wind speed, TWS is the true wind speed and TWA is the true wind angle. In the same way, the apparent wind angle (AWA) is:

$$AWA = \arccos\left(\frac{\left(TWS \cdot \cos\left(TWA\right) - BS\right)}{AWS}\right) \qquad \textit{Equation 2}$$

With these two equations, the viability study of a combined propulsion system can be started. First it must be analyzed, at a constant boat speed, the true wind necessary to generate a positive contribution of a sail. That is, the true wind speed which generates apparent wind angles under 140º at that boat speed. At 5knots of boat speed the true wind speed should be at least, over 4 knots. At 13 knots of boat speed, the true wind speed should be over 9 knots. At 30knots of boat speed, 20 knots of true wind speed would be required. Therefore, the faster the boat the higher true wind speed needed to generate an apparent wind angle in the usable range.

It must be highlighted the difference between a sailing boat and a conventional vessel combined with a sail. A sailing boat navigates thanks to the air thrust. The aerodynamic force generated by the wind should be larger than the hydrodynamic resistance. When a boat is at rest, and the real wind starts to interact with the sail, the aerodynamic force begins to increase. If it is large enough, the boat would start to move until the aerodynamic force was equal to the hydrodynamic resistance. Once the balance between forces is achieved, the boat navigates at constant speed.

A sailing boat navigates as fast as the wind allows her depending on the course which is constantly modified to optimize the boat speed. A commercial vessel enforces a constant speed and course because there is a schedule to fulfill. When a vessel is fitted with a sail the aim of the combination is the reduction of fuel consumption rather than increasing the boat speed. Normally, the boat speed and the course are kept constant and as the contribution of the sail improves, the contribution of the main engine is reduced and consequently, the fuel consumption is also reduced.

4.- Methodology

In order to study the viability of using a sail combined with a conventional propulsion system, three main steps must be analyzed.

Step 1: Wind study. First, the wind intensity, direction and occurrence probability should be studied. The wind is the source of this power and it should be guaranteed at least in a certain level before a deep research begins.

Step 2: Sail performance. Once the wind at the navigation area is considered appropriate, the sail performance is studied. The forces and moments which are provided by the sail are studied in this step.

Step 3: Power saving. In the last step, the combination of the wind in the navigation area and the sail performance is carried out. Here, the course of the vessel is taken into account, as well as the constant vessel speed.

As mentioned before, the case in study as an example is a structural sail of a cargo vessel. In the following, these three steps will be applied to this vessel in a certain navigation route.

5.- STEP 1: Wind Study

The wind is an endless energy source but it must be studied if the intensity, direction and occurrence probability is appropriate for the purpose. The wind at this step is the true wind (TW). The speed and direction of the wind should be then related to the boat speed and the route which is done at the third step. In the third step, the apparent wind (AW) is calculated. But first, the wind study is performed.

There are several databases which provide information regarding the wind characteristics. The data come from meteorological stations or the information provided by vessels. Nowadays, there are different numerical prediction programs which estimate the wind characteristics in a specific area.

Height of Waves (m)	Wind Speed (knots)
0-1	0-13
1-2	13-19
2-3	19-24
3-4	24-30

Table 1: Connection between waves and wind speed

A very well known data source used in the maritime field is the Global Wave Statistics (GWS) [7]. 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 which is shown on table 1.

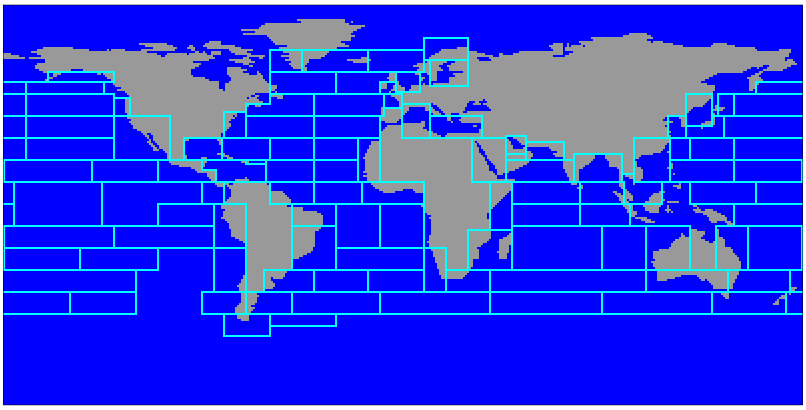

Figure 9: Wave Statistics, world area division

The seas and oceans are divided in different areas as shown in figure 9. 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 ($Prob_{wind}$ in equation 4).

If a route in the Bay of Biscay is chosen it would be included in the area 17 of the Global Wave Statics. The cargo vessel of the example navigates from the North-West of Spain to the South-West of France which is inside the area 17. It is assumed that the wind characteristics are the same in the whole area. In table 2 the annual probability of the wind speed is included. Furthermore, in table 3, the annual probability of wind direction is presented. It is considered an appropriate wind intensity since the range of normal vessel speeds of the cargo vessels in study, would be under 15 knots. As mentioned before, for 13 knots of vessel speed, true wind speeds above 9 knots are needed which is very reasonable according to the table.

Wind Speed (knots)	Probabilities (%)
0-13	12
13-19	29
19-24	25
24-30	16

Table 2: True wind speed annual probability at the Bay of Biscay Route

Direction	S	SE	E	NE	N	NW	W	SW
Anual Probability (%)	13	7	10	11	8	13	17	16

Table 3: True wind direction probability at the Bay of Biscay Route

Using this simple study as a starting point, there are some improvements than can be done. One of the first assumptions is that the wind intensity is constant in height but within the atmospheric boundary layer there is a wind gradient. In reference [8] it is explained how this profile can affect sail performance. Another improvement is the inclusion of gusts in the consideration of the wind. Moreover a detailed description of the wind at small areas should be carried out for advance researches. The wind is completely different inside a port, near the cost or at open seas.

6.- STEP 2: Sail Performance

Once the wind is considered appropriate, the sail performance is analyzed. There are five methods to estimate the behavior of a sail in an airflow: theoretical formulas, computational fluid dynamic (CFD) simulations, wind tunnel tests, regressions based on past information or full scale tests. The choice among them depends on the stage of the project, the budget and the tools/facilities available. Anyway, the best procedure is the combination of, at least, two methods.

The output of any of these methods should be the relation between the aerodynamic forces and moments with the apparent wind. The boat speed can vary, as well as the true wind, but the wind that the sail “sees” is the apparent wind. Therefore, the aim of these methods is to clarify the dependency of the performance with the apparent wind. For this purpose, the force coefficients (CF) and the moment coefficients (CM) are defined as follows:

$$CF = \frac{F}{1/2 \times \rho \times S \times V^2}; CM = \frac{M}{1/2 \times \rho \times S^{3/2} \times V^2} \qquad \text{Equation 3}$$

where “F” is the force in Newtons, “M” is the moment in Newton·meter, “ρ” is the air density in kg/m^3, “S” is sail area in m^2 and “V” is the apparent wind speed in m/s.

The structural sail of the example has been studied with a computational fluid dynamic software. The CEHINAV research group has calculated the force given by this sail with the CD- Adapco's STAR-CCM+ 5.04.006 program [9], which is a Reynolds Averaged Navier Stokes Equations based solver. The sail has 75m of span and $5375m^2$ of sail area. As results of these calculations, the three forces coefficients and three moment coefficients have been obtained.

In figure 10, the longitudinal force coefficient (CX), side force coefficient (CY) and vertical force coefficient (CZ) are plotted against the apparent wind angle (AWA). As it was expected the side and vertical forces contribution is considerably lower than the longitudinal force.

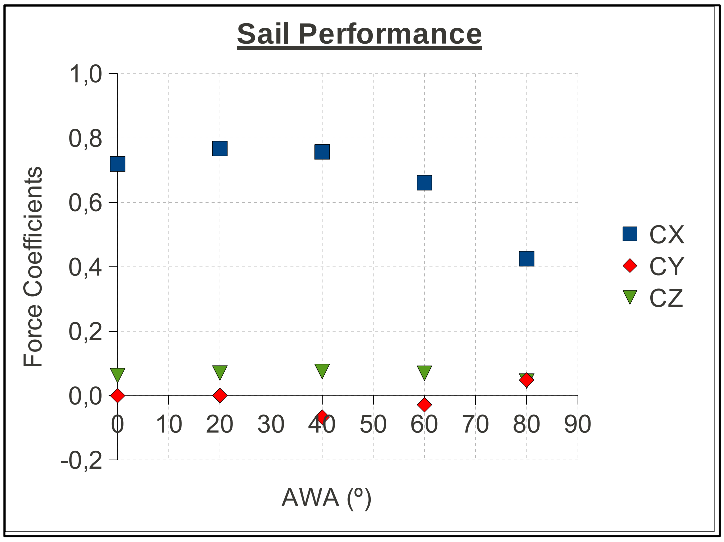

Figure 10: Sail performance, force coefficients

The calculations of this study have been run at an Intel® CoreTM i7-920 Processor with a Linux 2.6.32-27 kernel. A typical simulation has required around 50 hours for a $4.5\cdot10^6$ element mesh. It has been supposed that the maximum apparent wind speed would be 40 knots at the inlet boundary condition and the apparent wind angle from 0º (from the stern) to 80º.

There are some improvements that can be developed in this step. As mentioned before, this numerical study should be combined with another method such as wind tunnel tests to validate the results. As well as in the previous step, the wind profile should be taken into account. In this step, when the wind profile is combined with the boat speed, a wind twist appears that can also be included in the CFD. But the major drawback is that the boat speed should be fixed at this stage if the twist is included. Another improvement is taken into consideration the dynamic behavior of the system. The wind varies in time (gusts) and the vessel moves on the water (seakeeping).

7.- STEP 3: POWER SAVINGS

At the last step, the integration of the wind in the navigation route and the sail performance is carried out. Here, the course of the vessel is taken into account as well as the boat speed. If both concepts (course and boat speed) are merged to the true wind, the apparent wind is obtained. Now that the apparent wind is known, thanks to the coefficients of the sail performance, the aerodynamic drive force is calculated. If the drive force is multiply by the boat speed, the power that can be saved is calculated (P_{saved} in equation 4).

The power than can be obtained from the sail depends on the probability of occurrence of the true wind as it has been explained in the first step. Therefore, this probability must be taken into account:

$$P_{sail} = \frac{\sum P_{saved} \times Prob_{wind}}{Prob_{sail}} \qquad \text{Equation 4}$$

where "P_{saved}" is the power saved at a certain true wind speed and angl, "$Prob_{wind}$" is the probability of having that true wind and "$Prob_{sail}$" is the total probability of using the sail. This last probability includes the limitations of hoisting the sail such as high wind speeds or non appropriate wind angles.

The CEHINAV research group has developed a program than can study the viability of using a sail as an auxiliary propulsion system combined with a conventional system. The program executes this third step. It reads the data from the CFD and the Global Wave Statistics information, and calculates the power that can be obtained and the probability of using the sail.

The cargo vessel in study has been analyzed with this program. In figure 11 the drive force that can be obtained at the Bay of Biscay route, for different vessel speeds, is plotted. Moreover, the estimated hydrodynamic resistance has been included for comparison. As it can be seen, below 10 knots of constant boat speed, the vessel could be propelled by the wind whereas from 10knots on, the fuel consumption could be reduced due to the wind contribution to the thrust. At 12 knots the aerodynamic drive force is the 65% of the hydrodynamic resistance. Whereas, it is 30% at 16knots of constant boat speed.

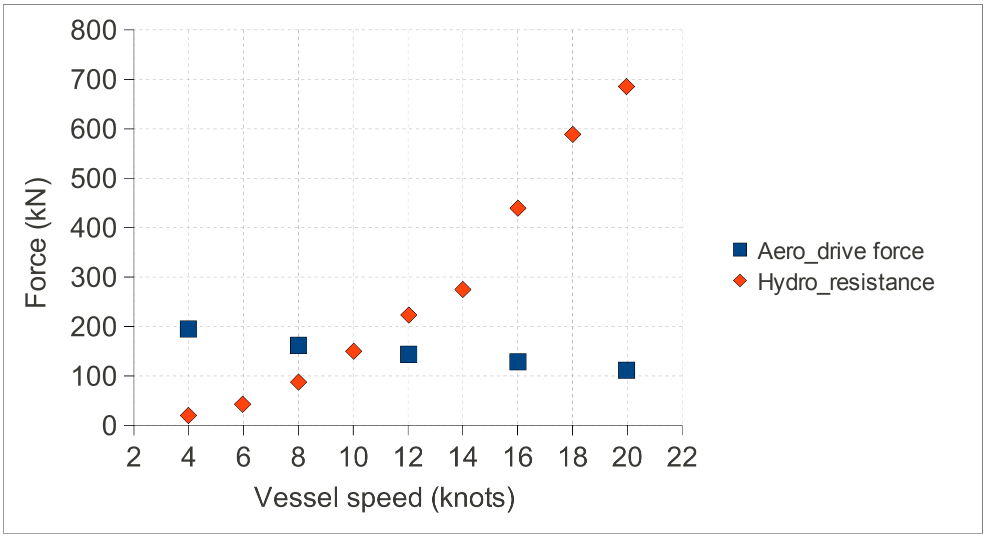

Figure 11: Hydrodynamic resistance and aerodynamic drive force

For each of the five points of the aerodynamic drive force that is included in figure 11 there is an annual probability of having that power. In table 4, the probabilities for each of the vessel speeds are presented. As it was expected, the higher the vessel speed the less usable the true wind is. It is concluded from the study of this cargo vessel that it could be saved power at medium speeds and even it could be propelled by the sail at low speeds for annual periods above the 50%.

Vessel Speed (knots)	4	8	12	16	20
Anual Probality (%)	53	51	47	41	37

Table 4: Probability of using the sail at the Bay of Biscay example route

In this step there are also some improvements that can be carried out. For example, the developed program could be transform into a Velocity Prediction Program (VPP) as the ones used in high performance sailing boats. This would imply adding the hydrodynamic data and finding the aero-hydro balance.

The structural analysis is not included in this paper since the viability study has been developed from an aerodynamic point of view. But it is obvious that the fourth step would be studying the structural performance of the sail due to the aerodynamics loads. Furthermore a very deep research on the hinges must be carried out in this type of sails due to the high magnitudes of forces and particularly, moments.

8.- CONCLUSIONS

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

- A methodology to study the viability of using a structural sail as a complementary propulsion system has been developed.
- It has been described the positive contribution of a sail to the reduction of fuel consumption.
- The presented methodology has been applied to a real scenario and the saved thrust has been quantified.
- The aim of the authors is presenting the ground for future deep studies related to structural sails.

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