Analysis of wind propulsion for cargo ships and workboats

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SUMMARY

Economic pressure, fuel prize increase and political wish to reduce green house gas (GHG) lead to consider alternative mean of propulsion for commercial ships.

In this paper are presented and analyzed various auxiliary wind propulsion systems intended to be used onboard commercial ships, taking into account operational constraints (size, safety, economy,...). All aspects of the problem are accounted for : aerodynamic performances, energy efficiency, impact of weather conditions and economical view.

A case study, carried out for a tanker shows the potential of auxiliary wind propulsion for commercial ships.

1. INTRODUCTION

Sails have been, up to the end of the XIXth century, the sole engine of merchant and working ships. Then, they have been quickly discarded to thermal engines and their use restricted to leisure and nautical sports, through yachting and competitive sailing.

The nearly continuous increase of oil price, which has dramatically accelerated for the last ten years (Figure 1), uncertainty about fossil fuel resources combined with the political realization about ecological consequences of massive green house gas (GHG) emission, lead to search for alternate means of propulsion for ships, cleaner and cheaper.

To fight against fuel price increase, the first measure taken by owners and operators has been to reduce ship speed (slow steaming). This allows also reducing GHG emission.

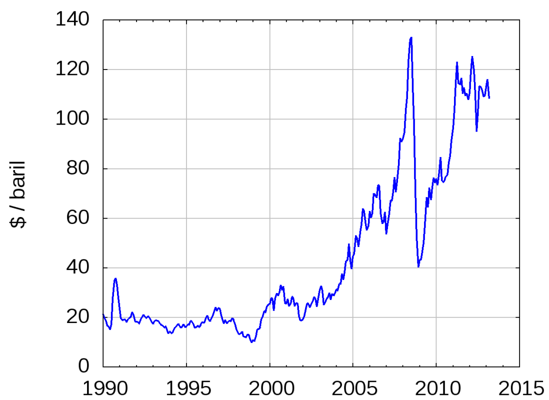

Figure 1 : Oil barrel price since 1990

European Union (EU) has unilaterally decided to cut in 2020 by 20% its GHG emission compared to the 1990 level. In 2012, countries of EU had already reduced by 18% their GHG emission [1] and are largely about to fulfill their commitment. On the other hand the International Maritime Organization (IMO) wish to limit the level of SOx to 0.5% by 2020 ; this would imply the generalized used of refined oil instead of crude oil with, as a consequence, an increase of 25% of fuel price.

If the politic will to reduce GHG emission appears to be real, this could happen only if the economical competitiveness is preserved. Wind is an inexhaustible source of energy, free, clean and available for ships. It looks then natural to search for a way to take advantage of wind energy. The revival of the age of sails doesn't look realistic, nevertheless, usage of a mean of propulsion, complementary to the main engine and its propeller that would decrease the overall energy consumption looks promising and worth being explored.

Classic sails are not the only mean to extract wind energy, wind mill are a good example. In the maritime field, wind driven alternative means of propulsion have had restricted diffusion and have not exceeded the state of prototype. The older one is the Flettner rotor named after its inventor and dates back to 1925, a simple rotating cylinder which, due to Magnus effect, allows creating lift and so propulsion. A second system is suction airfoil, based on boundary layer suction in order to increase section lift. This principle, well known from aerodynamicists, has been studied for ages in the aeronautic field before being transposed to the maritime domain through the impetus given by Commandant Cousteau who fitted his ship Alcyone with this system (Figure 4).

Both above wind propulsion systems have the distinctive feature, at the contrary of traditional sails, to require input energy. An engine is required to rotate rotor Flettner and a fan is necessary for boundary layer suction.

Those systems have not been industrially developed ; their economic interest was still not sufficient despite 1973 first oil crisis.

Some others systems have also more recently came out such as dynamic kite which shows interesting properties.

Auxiliary wind propulsion system will have to match today's requirement of ship operations, its setup shall match stability and maneuverability criteria, its size on deck shall be compatible with ship operations, loading and unloading and the crew shall be able to run the system without specific knowledge.

Using a wind propulsion system shall be safe for the ship and its crew in any circumstances, it shall also match marine rules and safety criteria.

At last, an auxiliary wind propulsion system have to match economical properties that allow promoting its distribution (initial cost, lifespan, maintenance,...). Several questions arise in the mind of the designer or owner that wish to consider these solutions :

- what are the performances of wind propulsion ?

- what are performances of a ship sailing an hybrid propulsion, using both its main engine and an auxiliary wind propulsion ?

- what are weather conditions or routes suitable to a ship fitted with an wind propulsion system ?

CRAIN, based on its experience in wind propulsion for leisure and racing yachts, and more generally in ship design has undertaken to answer some of these questions and to develop tools that allow studying hybrid propulsion solutions for ships.

A part of the work presented here has been carried out in the frame of the collaborative FP7 project ULYSSES [5] partly funded by the European Commission and also in the frame of an internal research program funded by the European Regional Development Fund (ERDF), MRES and Région Poitou Charente. This work also benefited from scientific partnerships with ENSMA Poitiers (wind tunnel) and La Rochelle University (CFD).

2. WIND PROPULSION SYSTEMS

In order to correctly understand the qualities of a wind propulsion system, it is necessary to recall some aerodynamic concepts and their involvement in sailing.

Aerodynamic forces split up into drag, parallel to the apparent flow direction and into lift, perpendicular to the flow direction. Without any external energy contribution, drag shows the same direction as the flow. While sailing fully downwind, drag is solely propulsion ; however this prevents the ship to sail upwind. Drag tends to move the ship backward as soon as apparent wind blows in front of its side. As for the second component, lift, it is fully propulsive when apparent wind blows from the side of the ship and is necessary to develop propulsion as soon as apparent wind blows in front of the side of the ship. The ability of ships to sail upwind depends on the lift to drag ratio ; a significant lift combined to a low drag is required (fig 2). This leads to a major conclusion about behavior of sailing boat which is that specifications of wind propulsion depend on wind direction. This is why a sailing yacht has different sails for each conditions. Nevertheless, capacity to develop a significant lift has proven to be the best way to produce a significant thrust in a wide range of conditions as soon as the lift to drag ratio remains satisfactory. The sole interest of drag is downwind, that was the way of sailing in the XVIIIth century.

One of the main drawback of traditional sails is the area required to develop a thrust sufficient for the ship to reach a honorable speed. This area, which is already substantial for a leisure yacht becomes considerable for a commercial ship. Unlike yacht, a ship can hardly be lighten without decreasing its payload capacity which is its reason for being. The size on deck of the wind propulsion system have to be limited, compatible with other deck equipment ; influence on the crew have to be as low as possible in terms of knowledge, security and workload.

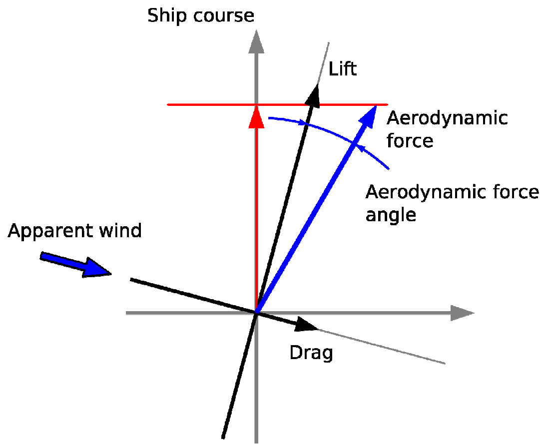

Figure 2: Aerodynamic force angle depending on apparent wind angle and lift to drag ratio

Aerodynamic force can be expressed as :

$$F = \frac{1}{2}\rho V^2 \cdot S \cdot C_f \qquad (1)$$

where V is the apparent wind speed, S the area and Cf a coefficient depending on operating conditions that could be either the lift coefficient or the drag coefficient according to the component taken into consideration.

In order to increase thrust on a sailing yacht, the solution is to increase sail area as apparent wind speed depends on conditions and aerodynamics, through lift and drag coefficients, depends on sail shape, trim and wind direction.

Here lies the interest of wind propulsion systems that can be considered on ships, so suction sections, rotors or dynamic kites.

Although the underlying physics of the two former systems is different[1], they show similar characteristics : a very high lift per area unit. Whereas the lift coefficient of a sail is about 1.5, lift coefficient for these two systems can reach 8 or 10 ; this is 5 to 7 times higher. To generate a given lift, they allow reducing the size of the system in the same ratio. This is a significant advantage when looking at the overloaded deck of ships.

The principle of kite is different. It is based on a standard kite wing, showing similar aerodynamic properties than a sail, but that moves at high speed on a predefined trajectory. Apparent wind speed is increased in this case and as it is squared in equation (1) this will lead to significant forces, much higher than the one of traditional sails for a similar area.

After describing guiding principles of wind propulsion systems, the question is now to assess aerodynamic and energetic performances of these systems. CRAIN has undertaken this work to answer questions of players in the maritime field.

2.1. Suction airfoil

The maximum lift that can be achieved by a wing section increases with thickness and camber. This is true until the flow is massively separated. This actually limits wing section thickness. The principle of the suction airfoil, developed as early as the 40's in the aeronautic

[1] There is very often confusion between Magnus effect and suction airfoil system

field and reused by L. Malavard [2] and B. Charrier applied to ship propulsion in 1980 (Figure 4), is to suck the boundary layer at the wall of the section in order to prevent separation and hence to bring back lift (Figure 3).

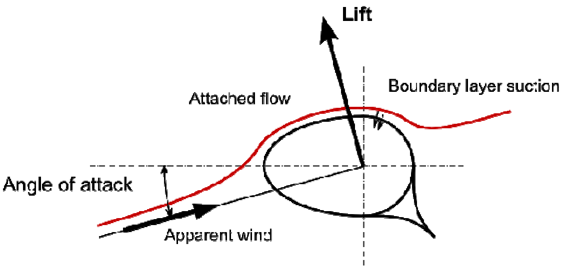

Figure 3 : Suction airfoil principle with boundary layer suction

Using thick section allows reaching a very significant lift, with lift coefficient in a order of magnitude of eight, so four to eight times greater than traditional sails.

Figure 4: Commandant Cousteau's Alcyone fitted with its suction airfoil of type Turbosail

Some energy is required to suck the boundary layer but propulsive power generated this way is almost significantly greater than the input, due to wind energy contribution. Figure 5 shows the ratio of propulsive power developed by suction airfoil system over the power used by the system to run, depending on apparent wind angle.

$$\eta = \frac{P_{prop}}{P_{cons}} \qquad (2)$$

with :

P_{prop} : propulsive power generated by the wind propulsion system

P_{cons} : power used by the system

In this example, ship speed is ten knots, true wind speed is twenty knots. Efficiency of the suction airfoil as a wind driven propulsion mean is greater than unity starting from 30° and maximum values of 10 are reached for wind angles about 150°. Having an efficiency greater than one stems from the fact that the energy used by the system is amplified by the use of wind energy. In that case, we prefer to talk of energy amplification coefficient more than efficiency.

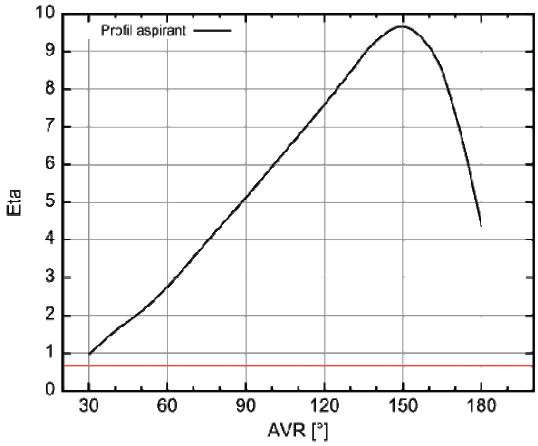

Figure 5 : Energy amplification by suction airfoil as a function of true wind angle

The red line shows the typical efficiency of a propeller. For all apparent wind angles shown on the chart, the suction airfoil wind propulsion system is more efficient than a conventional propeller. Nevertheless, and that is the case here, a wind propulsion system of a size that is consistent with ship dimensions is not able to propel the ship at the selected speed in every conditions ; nevertheless overall consumption can be dramatically reduced depending on wind conditions and wind system size.

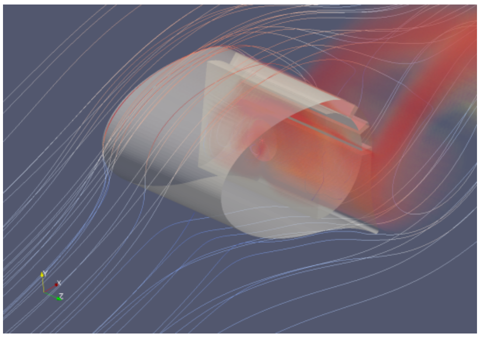

Figure 6 : CFD flow around a suction airfoil

2.2. Flettner Rotor

Flettner rotor is based upon Magnus effect. When a cylinder rotates in a flow, fluid accelerates at the top and slows down at the bottom, due to friction (Figure 7). As the fluid accelerates, pressure decreases at the top and vice-versa at the bottom. This pressure variation generates lift.

A huge lift can be generated this way with bidimensional lift coefficient up to 10 in favorable conditions. This lift magnitude can be achieved due to the energy contribution required to rotate the cylinder. Nevertheless, as for suction airfoil, the propulsive efficiency, calculated over the energy required to run the system is greater than one and we can also talk of amplification of energy.

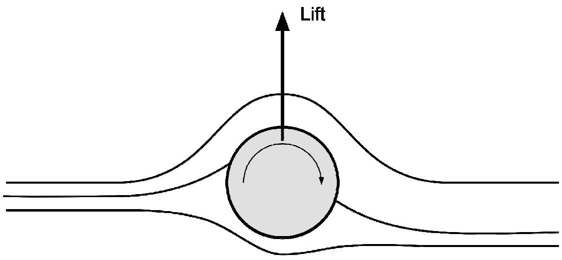

Figure 7 : Rotating cylinder principle

Many studies deal with rotating cylinders such as the work of B. Charrier [3] that gives lift and drag coefficients as a function of rotational speed. Nevertheless, few experimental figures for rotating torque are available, especially when fitted with end plates.

Cargo ship "E-Ship 1" (Figure 8) is currently fitted with four Flettner rotors.

Figure 8: E-SHIP 1, fitted with four Flettner rotors

2.3. Dynamic kite

Use of kites for ship propulsion is based on apparent wind speed increase on the wing. To achieve that, the kite needs to move constantly, following a given trajectory at the highest possible speed. Aerodynamic properties of kite wings are similar to the ones of traditional sails. Without any movement of the kite relatively to the ship, forces developed by a kite would be of the same order of magnitude of the ones of a sail of the same area. A slight increase may nevertheless happen for a static system as wind speed increase with altitude, for example, wind speed increases by 50% from a 10 meters height to a 100 meters height. Despite that, kite area that could propel significantly a ship would be so huge that the system required to keep the kite flying is a serious technological challenge.

On the other hand, a kite can keep moving at high speed relatively to the ship, this is the so called dynamic kite. Underlying physics has been described, Dadd [4] is an example. We have developed SIMKITE, our simulation tool that models dynamic kite physics and behavior. For example, this tool allows assessing inertia effects that occur using large kite. Dynamic kites dedicated to ship propulsion are produced and tested on cargo ship by SkySail company [5] (Figure 10). Dynamic kite can reach speed of 200 km/h, leading to lift coefficients, based upon wind speed, from six to ten times higher than the one of a stationary kite ; area can be then reduced in the same ratio for a given thrust.

The kite is connected to the ship by a towing line that transmits kite forces to the ship. The length of this cable is constant, this defines a flight envelop which is a quarter of a sphere, oriented according to the apparent wind on which lie kite trajectory (Figure 9).

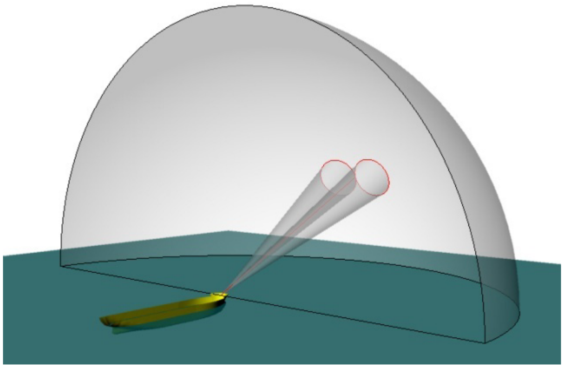

Figure 9 : Downwind flight envelop and trajectory of a dynamic kite

Kite ability to accelerate increases as it is located in the middle of the flight envelop. Running downwind, flight envelop axis is aligned with the ship axis, hence leading to maximum thrust ; when apparent wind blows from the side, the flight envelop is also transverse to the ship but there is no propulsive force in that direction. So the kite needs to fly toward the bow, on a side of the flight envelop where efficiency is greatly reduced. This means that kite are especially efficient downwind but that generated thrust drops down very quickly as the apparent wind angle decreases.

One of the main parameters about efficiency of this system is the lift to drag ratio of the wing itself. Higher is the lift to drag ratio, lower is the drag of the wing and greater is the achievable speed (flight speed is roughly proportional to the lift to drag ratio). Hence, apparent wind speed is increased as well as aerodynamic forces.

The main technological challenge with this system is to have an automatism able to control kite flight, to keep it on an efficient trajectory, to manage launch and recovery operations, taking into account ship operational conditions (8000 h/year, reduced crew,...)

Figure 10 : Cargo ship propelled by a dynamic kite (image Skysails)

2.4. Performance comparison

Various criteria have to be accounted for in order to compare potential performances of wind propulsion systems :

- thrust per area unit which shows the size of the system and its acceptability
- energy consumption which influences ship global energy efficiency
- lift to drag ratio which shows ability of the system to work in upwind conditions

Static systems, such as multi-elements thick airfoil allows in the best case doubling the thrust compared to traditional sails. No contribution is required and lift to drag ratio is good.

A dynamic system, such as dynamic kite can produce ten times more thrust per area unit. Size on deck is minimum. On the other hand, lift to drag ratio is poor, so it is efficient solely downwind. This also assume to have a system able to manage properly the kite in use.

Static and active devices such as rotating cylinder, airfoil with boundary layer control (suction, blow jet,...) can increase thrust by a factor 4 or 5 but they need energy and their lift to drag ratio is limited. They can be easily automated.

Rotating cylinder has been studied for years. Thrust can be high but the lift to drag ratio is quite poor. This can be improved by fitting a end plate but energy consumption becomes high.

Boundary layer suction has also been studied for a long time in the aeronautic field. It has been put into practice once on board

Commandant Cousteau's Alcyone as the so-called Turbosail. Unlike rotating cylinder, performances depend on a lot of design parameters that influence internal and external flow quality.

Looking only external aerodynamics, so lift, drag and suction power coefficients, Malavard's [2] experimental results show that the suction airfoil concept has a greater potential than rotor in terms of energy consumption and lift to drag ratio. Actually, this depends strongly on the quality of internal flow.

That is the reason why we have resume the study of the suction airfoil taking into account internal flow by the mean of wind tunnel tests and CFD.

This article is not about this work but we can mention that results, could they be confirmed by full scale experiments, reveal that the suction airfoil concept allow using wind propulsion with very interesting performances in term of energy, economy and acceptability.

Table 1 shows orders of magnitude so that the various concepts can be compared. Reference is a four suction sails system, described below showing a height of 24 meters which has been adopted for all the other systems. Area have been adjusted to provide the same aerodynamic force for all the systems and this for apparent wind angle in a range from 40° to 120°. The direction of the aerodynamic force relatively to the apparent wind direction is a function of the lift to drag ratio (Figure 2).

	Area	Aerodynamic force angle	Energy consumption
Sails	2100 m²	33°	
Symmetrical thick section	2500 m²	22°	Null
Two elements asymmetrical thick section	1250 m²	19°	Null
Suction airfoil	400 m²	19°	Moderate
Flettner Rotor fitted with end plate	390 m²	23°	High
Dynamic kite	300 m²	49°	Null

Table 1: Informative properties that may vary depending on technical solution for each of the systems

3. PERFORMANCE PREDICTION OF SHIP USING AUXILIARY WIND PROPULSION

The preceding section has shown wind propulsion system properties without taking into account the ship on which it is fitted. Then, the ship using a wind propulsion system has to be studied depending on weather and operational conditions the ship is facing.

So far, performance predictions of sailing and motor ships were based on separate methods, although some similarity exists.

For motor ship, the method is to predict the required engine power as a function of ship speed. The efficiency of each component of the propulsive chain has to be assessed in order to evaluate the global efficiency, which is the ratio of propulsive power over engine power.

Sailing yacht performance prediction is carried out using software called VPP (Velocity Prediction Program). This models compute balance of aerodynamic and hydrodynamic forces for at least three components. Initially, this kind of software aimed to predict yacht speed as a function of wind conditions (wind speed and wind angle relatively to the yacht), and this justifies the name of this type of program, delivered outputs also include all operational parameters of the yacht (heel angle, yaw angle, aerodynamic coefficients of sails and appendages,...)

In the case of hybrid propulsion, both approaches have to be combined in a single tool that models physics of both motor ships and sailing yachts, plus complications coming from interactions between the two means of propulsion.

Going one step further and to answer more global energetic issues, the need to model the whole chain becomes obvious. Innovative solutions appears for which the number of systems increases as well as their variety. for example, onboard energy can be supplied by one or more generators, by photovoltaic boards, by a fuel cell,... The ship will be modeled as a collection of sources, consumers, converters and storages linked together.

Based on its experience in design and realization of performance prediction software, CRAIN has developed SIMWP a modular tool able to take into account a large variety of ship configuration. It has been designed to quickly integrate new and innovative energetic systems. SIMWP can assess hydrodynamic and aerodynamic aspects as well as energy transfer and efficiency on board a ship.

The number of parameters in such a system becomes quite large, moreover each system has its own operating limits, in terms of power or temperature for example,... So the tool developed at CRAIN has been designed to optimize operating parameters in order to improve efficiency based on user defined criteria, taking into account a set of constraints that can be related to equipment, security,...

For example, optimization is required for the following parameters : wind propulsion operating power and efficiency, propeller pitch if adjustable, propulsive force direction,...

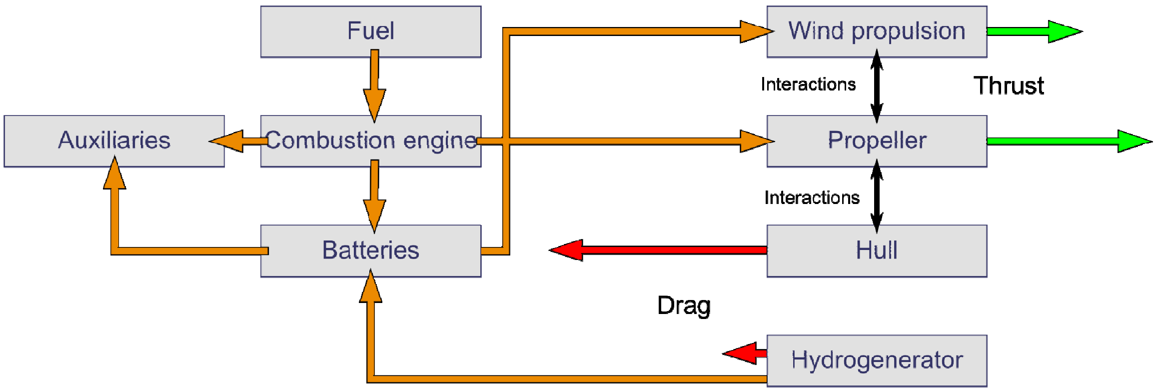

Figure 11 : Energy flow and forces as modeled in the prediction performance program

4. ROUTE OPTIMIZATION

Savings from wind propulsion depends significantly on weather conditions. A cargo ship need to comply with its time schedule, then it may take the most favorable route depending on one or more criteria (consumption for example) and a set of constraints. It is then obvious to assess this contribution into a wind propulsion study.

Weather routing is commonly used by competitors in offshore sailing. In this case, the objective is minimum sailing time.

In the frame of weather routing for cargo ships using wind propulsion, the problem is different as journey time is set by commercial priorities. Nevertheless, ship speed and course can be adjusted to minimize a criterion that is not travel time any more but, depending on the project, consumption, polluting or green house gas emission, cost,... Algorithms that are traditionally used for sailing yachts weather routing are not valid anymore, so we have developed a specific algorithm that deals with hybrid propulsion and more generally with multi-criteria route optimization.

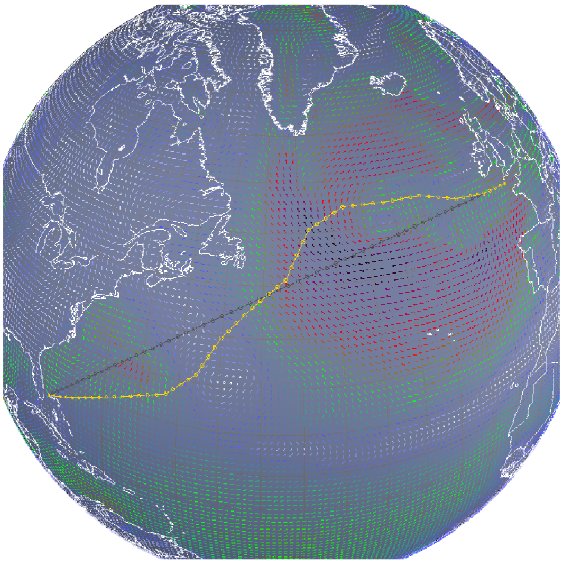

Figure 12 : Example of weather routing using hybrid propulsion

It will be shown later in this paper that savings coming from wind propulsion can be doubled if we assume that the ship always takes optimum route. This has been assessed as the average of optimum routes for a large set of trips using real (not statistical) weather conditions.

5. CASE STUDY

Some of the figures presented here are partial and provisional results obtained in the frame of ULYSSES project which deals with reduction of green house gas emission for cargo ships. This project is still ongoing and specific communications will be made by other stakeholders.

ULYSSES project

The topic of this project is reduction of ship service speed (slow steaming) applied to tankers and bulkers. Slow steaming allows decreasing fossil fuel consumption et green house gas (GHG) emissions.

ULYSSES Project objectives are :

- assessment of slow steaming impact on environment (fossil fuel, GHG emission) and economical sustainability.
- various ways of improvement for ship using slow steaming (retrofit and new buildings)

This project has gathered a set of partners covering all the fields of expertise required :

- engine and propulsion
- resistance, sea keeping, maneuverability
- structural design
- maritime rules and safety
- computational and experimental aerodynamics
- wind propulsion
- route optimization
- owners and charterers

The study carried out in the frame of ULYSSES takes into account :

- Necessity to sustain a flow of goods and consequences on capital investment and operational cost (capital asset for ship and goods, crew wages,...)
- efficiency of current propulsion systems at low speed and possible progress
- maneuverability and safety issues in bad weather

This study has been successively carried out for :

- six typical tankers (estimation only)
- REF : an existing tanker, Torm Lilly (handimax)
- 2020 project : a tanker with the same payload capacity for which hull shape and propulsion have been improved for slow steaming on the basis of available short term technologies
- 2050 project : concept of a tanker using a set of innovations currently developed by partners or else, applied to general design, engine and propulsion.

Main particulars of REF are as follow :

Type	Tanker Handymax
Dimensions	183m x 32m

Deadweight (dwt)	53 000 t
Service speed	15 knots

Table 2 : Main particulars of Torm Lilly

Figure 13 : Torm Lilly

Evaluation have been carried out for REF and its evolutions not only using a 100% fuel propulsion but also using mixed fuel and wind propulsion. Three types of wind propulsion system have been assessed at each phase of the project :

- suction sail (CRAIN)
- Flettner rotor (SSPA and Chalmer Univ)
- Dynamic kite (CRAIN & SSPA)

Safety issues related to wind propulsion, especially about stability and maneuverability, have been addressed.

Sizes of wind propulsion systems have been chosen to comply with availability on deck, safety issues and to offer a good trade-off between environmental and economical profitability.

Evaluations have been carried out for a trip from Rotterdam to New-Orleans, with ship fully loaded outbound and in ballasted state on its way back. It is based upon historical weather conditions for the last ten years that have been provided by the European Centre for Medium Range Weather Forecast (ECMWF). This method allows using real weather data contrary to statistical weather data. This way allows preserving structures and sequences of weather systems ; finally results have been averaged over the whole set of simulated data.

Consumption prediction using propeller have been base upon tank test and simulation carried out by SSPA, using internal code SEAMAN plus full scale measurement on existing ship Torm Lilly gathered by Wartsila. These simulations model swell and ship windage. Efficiency of combustion engine has been studied by Wartsila, TNO and Newcastle University. The cost model has been done by Bureau Veritas and Germanisher Lloyd.

In this cost model, fuel price is one of the decisive parameter. ULYSSES project has selected three price scenario :

Marine oil price		
High	1275 USD/t	2050 high projection
Average	898 USD/t	2050 low projection Expected before 2020 (*)
Low	520 USD/t	2013

Table 3 : Fuel price scenario

(*) this fuel price is equivalent to the total replacement, scheduled for 2020, of IFO crude oil by MGO distilled oil.

Slow steaming using fuel only

Figures given in this section are only indicative and cannot be considered as final results of ULYSSES project which is still ongoing.

The structure of the global cost for given distance and payload, as a function of mean speed is shown on Figure 14 (this sample is an intermediate result for REF ship, fully loaded on a 3000 nautical miles long trip and an average fuel price).

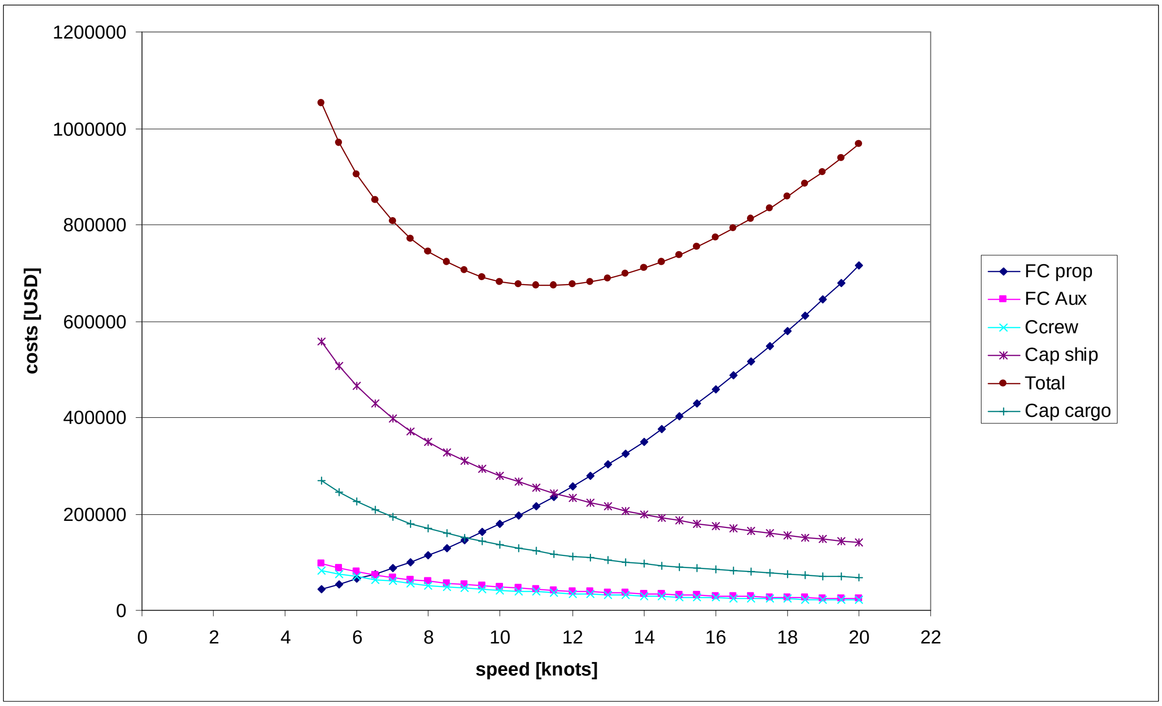

Figure 14: Cost distribution as a function of average speed and economical optimum (origin ULYSSES, Bureau Veritas)

FC prop : Propulsion fuel consumption

FC Aux : Auxiliaries fuel consumption

Ccrew : Crew wages

Cap ship : Ship depreciation cost

Cap cargo : Inventory capital cost

In this example, the best economical average speed is around 11 knots whereas current service speed is 15 knots.

Table 3 shows optimum speed given for various payload and fuel price cases.

	V_{opt} high fuel price	V_{opt} average fuel price	V_{opt} low fuel price
Ballasted	9 kt	10 kt	12 kt
Laden	10.5 kt	11.5 kt	14 kt

Table 4 : Economical optimum average speed depending on fuel price

These results indicate that a reduction of average service speed is to be considered ; this tendency is similar for other tankers of different sizes.

Assessment of "suction" wind propulsion

Here we show results for REF ship fitted with the following wind propulsion configuration :

Wind propulsion system	Suction wing developed at CRAIN
Number of wing	4
Wing span	24m
Single wing area	96 m²

Table 5: Wind propulsion particulars

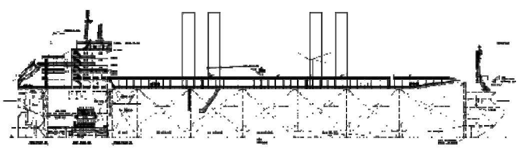

Figure 15 : Side view of Torm Lilly tanker fitted with four suction sails

Fossil fuel savings

As seen above, computation of consumption savings is based on a return trip from Rotterdam to New-Orleans.

Calculations are carried out :

- on the direct route
- on a route that optimizes fuel consumption depending on weather condition for ten years
- for average speeds of 8, 10 and 12 knots

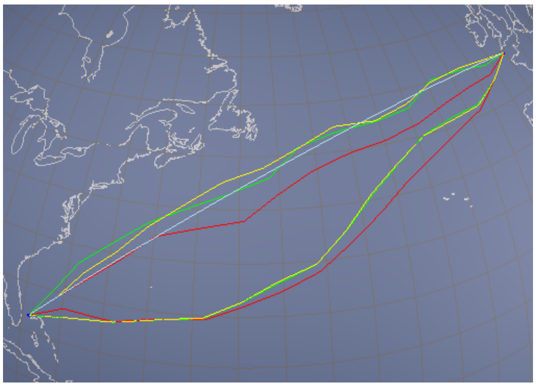

Figure 16 : Sample of optimized routes, return trip using auxiliary wind propulsion

Table 6 shows net fuel saving relatively to a ship not using wind propulsion.

Average speed (kt)	8	10	12
Direct route	20%	14%	7%
Optimized route	33%	26%	12%

Table 6 : fuel consumption saving by using wind propulsion

Average daily fuel consumption for various configurations is given in table 5.

Average speed (kt)	8	10	12
Direct route without wind propulsion	8,6 t/j	14,9 t/j	23,3 t/j
Optimized route using wind	5,7 t/j	11,1 t/j	20 t/j
fuel saving	2,9 t/j	3,8 t/j	3,3 t/j

Table 7 : Daily propulsion fuel consumption

Remarks :

- absolute value of fuel saving variation is maximum around 10 knots. This mainly comes from average apparent wind angle and speed variation.
- Route optimization has a significant effect. Nevertheless, this has to be moderated in real life because a perfect optimization would assume two or three weeks long weather forecast, depending on average speed. On the other hand, route optimization can also be used for ship without wind propulsion since swell, waves and wind have a significant effect on this kind of ship. Influence of weather routing without wind propulsion is given in table 6.

Average speed (kt)	8	10	12
Saving	12%	11%	5%

Table 8 : propulsion fuel consumption saving by sailing an optimized route (without wind propulsion)

- Although it has already been accounted for in the energy saving calculation, wind propulsion fuel consumption is an interesting figure (Table 9).

Average speed (kt)	8	10	12
Wind propulsion consumption	2%	1,3%	0,8%

Table 9 : % of total fuel consumption used by wind propulsion

Average energy consumption of wind propulsion is 20% of propulsive energy supplied. Average amplification factor, calculated using equation (2) is 5.

Financial profitability

The number of sailing days per year is calculated as a function of average speed with 4 days of stopover per return trip. This leads to the net fuel saving through using wind propulsion. Weather routing efficiency is taken as 0.7.

Average speed (kt)	8	10	12
Fuel saving (t/year)	792	1055	735

Table 10: Annual fuel saving due to wind propulsion

We have calculated, for the studied system, acquisition and additional costs :

- refitting (existing ship)
- shipping
- installation
- maintenance
- financial cost
- weather routing cost

The initial cost of wind propulsion depends on parameters such as engineering level, effective lifespan, financial costs..., we have estimated this cost between 350 k$ and 600 k$ per year.

Then, profitability of wind propulsion can be shown on chart Figure 17. Annual cost of wind propulsion is located inside the orange rectangle, this means that the system becomes profitable as fuel saving curve is located above annual cost curve (green block).

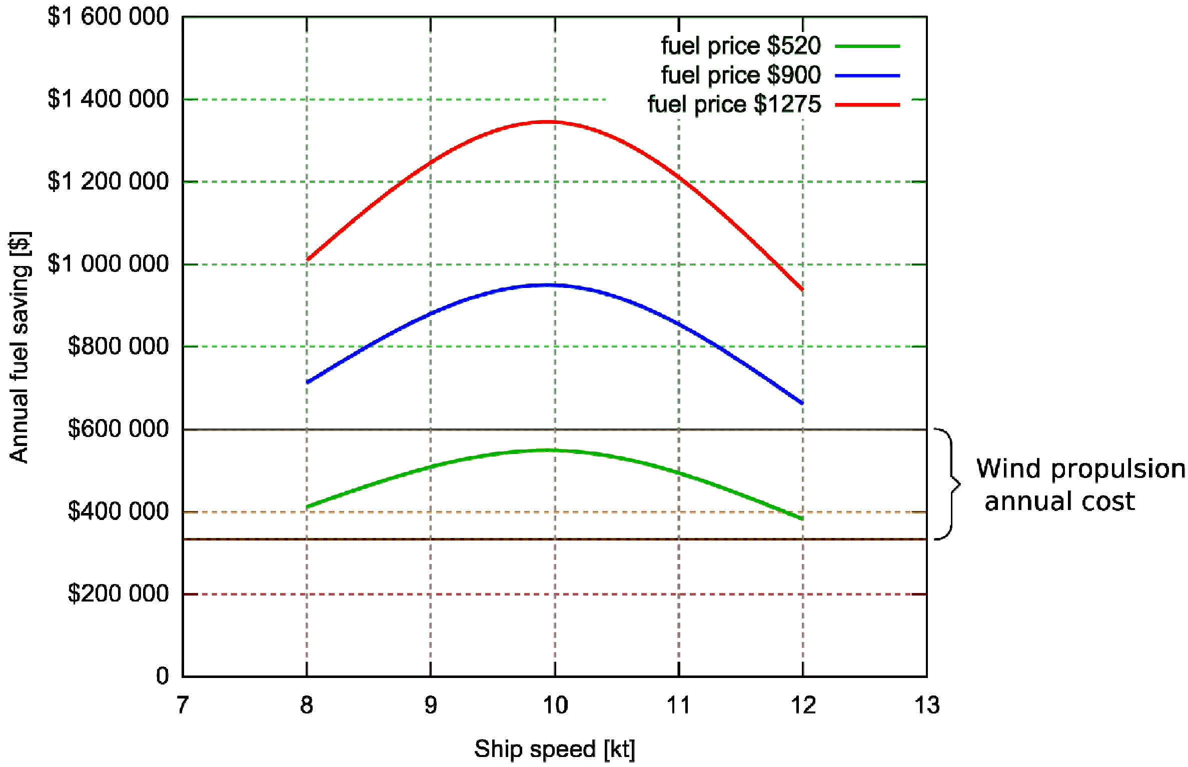

Figure 17: Wind propulsion financial balance

We can deduce from this chart that :

- studied wind propulsion system could be profitable with current fuel price (600 $ per ton)
- studied wind propulsion is much more attractive when combined with slow steaming at an optimal average speed of 10 knots
- wind propulsion will be significantly profitable by 2020 since crude oil is going to be gradually replaced by MGO distilled oil.

6. CONCLUSIONS

In this paper, we have described some properties, a method and some tools that allow analyzing energetic and economical interest of wind propulsion applied to cargo ships. Results of this analyze have been provided for a typical case.

A comparison of various wind propulsion systems properties has been carried out, based on computational and experimental data.

We have described aerodynamic properties of a tool able to provide, for each wind and wave conditions, propulsive contribution as well as energy saving for a ship using hybrid propulsion. This tool can also analyze influence of wind propulsion on ship hydrodynamics and combustion engine. It provide optimum operating points based on consumption. This results can then be used for weather routing.

In the specific case of suction airfoil wind propulsion that we have studied, we have shown, using those tools, that auxiliary wind propulsion can reduce significantly average fuel consumption and so GHG emissions for a tanker operating on a commercial route. Influence of average ship speed and of route optimization on fuel consumption have been shown.

The financial profitability of wind propulsion has been analyzed taking into account, in the case of suction airfoil wind propulsion that we have studied, the whole of associated costs and their variability. This analyze shows that wind propulsion could be already cost-effective using a system practically acceptable. Profitability can only be improved in the future because of fuel price increase and of wind propulsion system standardization.

Auxiliary wind propulsion appears as a method that could reduce dramatically GHG emission of marine traffic. It can be practically used on existing ships, with a profitability that can only increase.

Its implementation requires to choose suitable wind propulsion systems for which energetic contribution and economic profitability can be assessed using the methodology we have described.

7. REFERENCES

[1] European Environment Agency – Trends and projections in Europe 2013 - Tracking progress towards Europe's climate and energy targets until 2020 – EEA Report No 10/2013

[2] L. Malavard - Un nouveau propulseur éolien de navire - Comptes rendus de l'académie des sciences, Tome 1, n°1, 1984

[3] B. Charrier - Etude théorique et expérimentale de l'effet "Magnus" destiné à la propulsion éolienne de navires - Thèse de Doctorat - Université de Paris VI - 1979

[4] G.M.Dadd, A. Hudson and R.A.Shenoi - Comparison of two Kite Force Models with Experiment. - Journal of Aircraft, Vol 47, n°1, Jan-Feb 2010.

[5] www.skysails.com

[6]www.ultraslowships.com